From Spitzer to Herschel and Beyond:
The Future of Far-Infrared Space Astrophysics
The Structure and Evolution of Galaxies
Tuesday morning June 8

Predictions from Galaxy Modeling

Joel R. Primack , UCSC

Outline

Topics — Collaborators

- Semi-Analytic Models (SAMs) Rachel Somerville

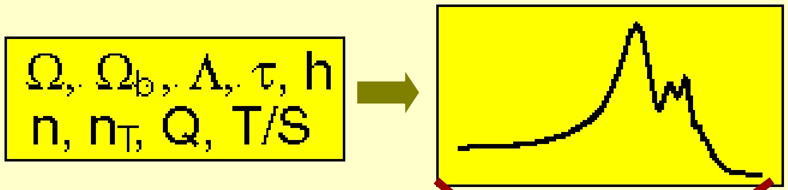
  Global predictions agree with data

  Colors are not predicted so well

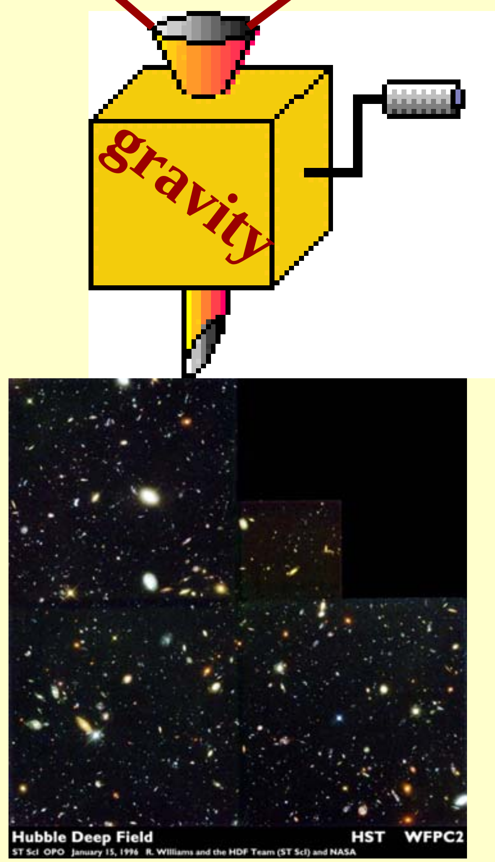
- Hydrodynamic simulations T J Cox, P Jonsson, & Rachel Somerville

  Large suite of galaxy mergers

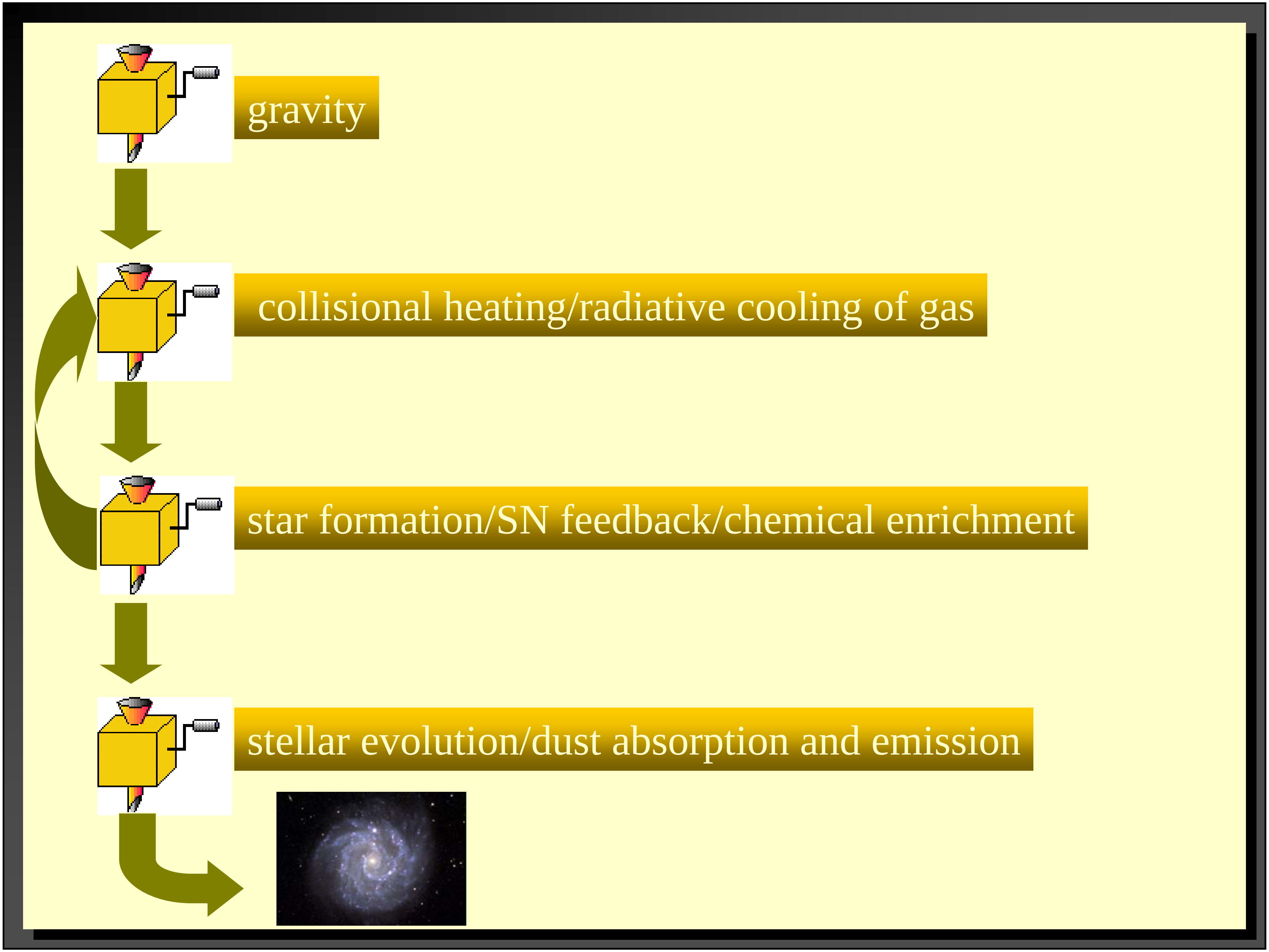
- New methods for comparing simulations to observations Jennifer Lotz & Piero Madau



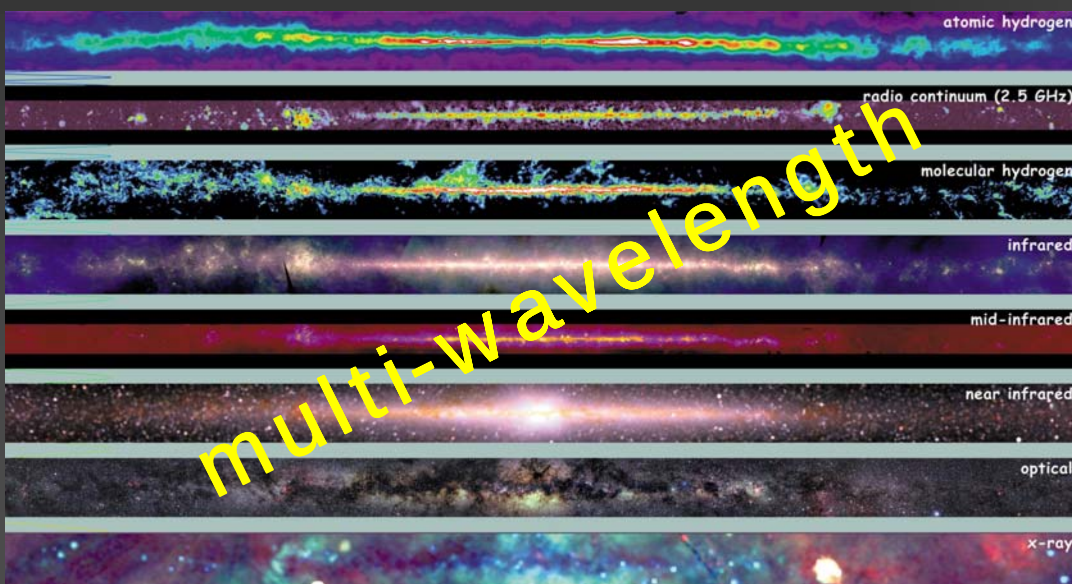
power spectrum



simulation by the VIRGO consortium


gravity
collisional heating/radiative cooling of gas
star formation/SN feedback/chemical enrichment
stellar evolution/dust absorption and emission

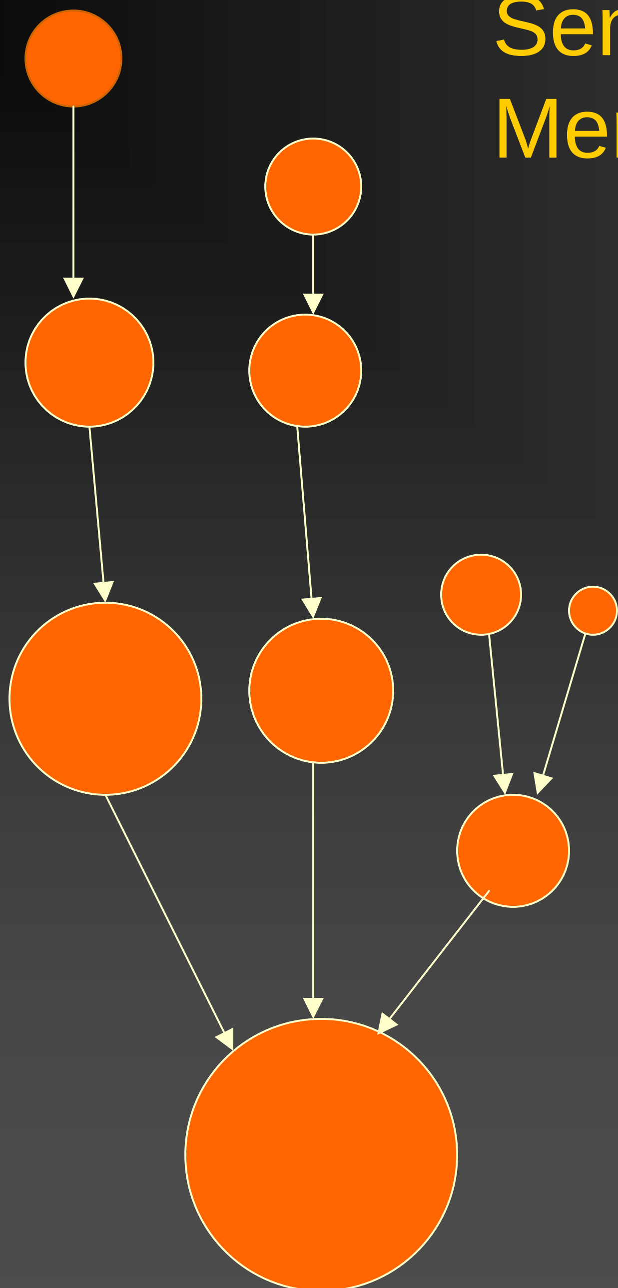
the challenge:



tools:

- collisionless N-body simulations
  - solve equations of gravity for particles of dark matter (& sometimes stars)
- hydrodynamic N-body simulations
  - solve equations of gravity and hydrodynamics/thermodynamics for particles of dark matter and gas
- semi-analytic models (SAMs)
  - treat gravity and “gastrophysics” via analytic approximations (bulk properties)

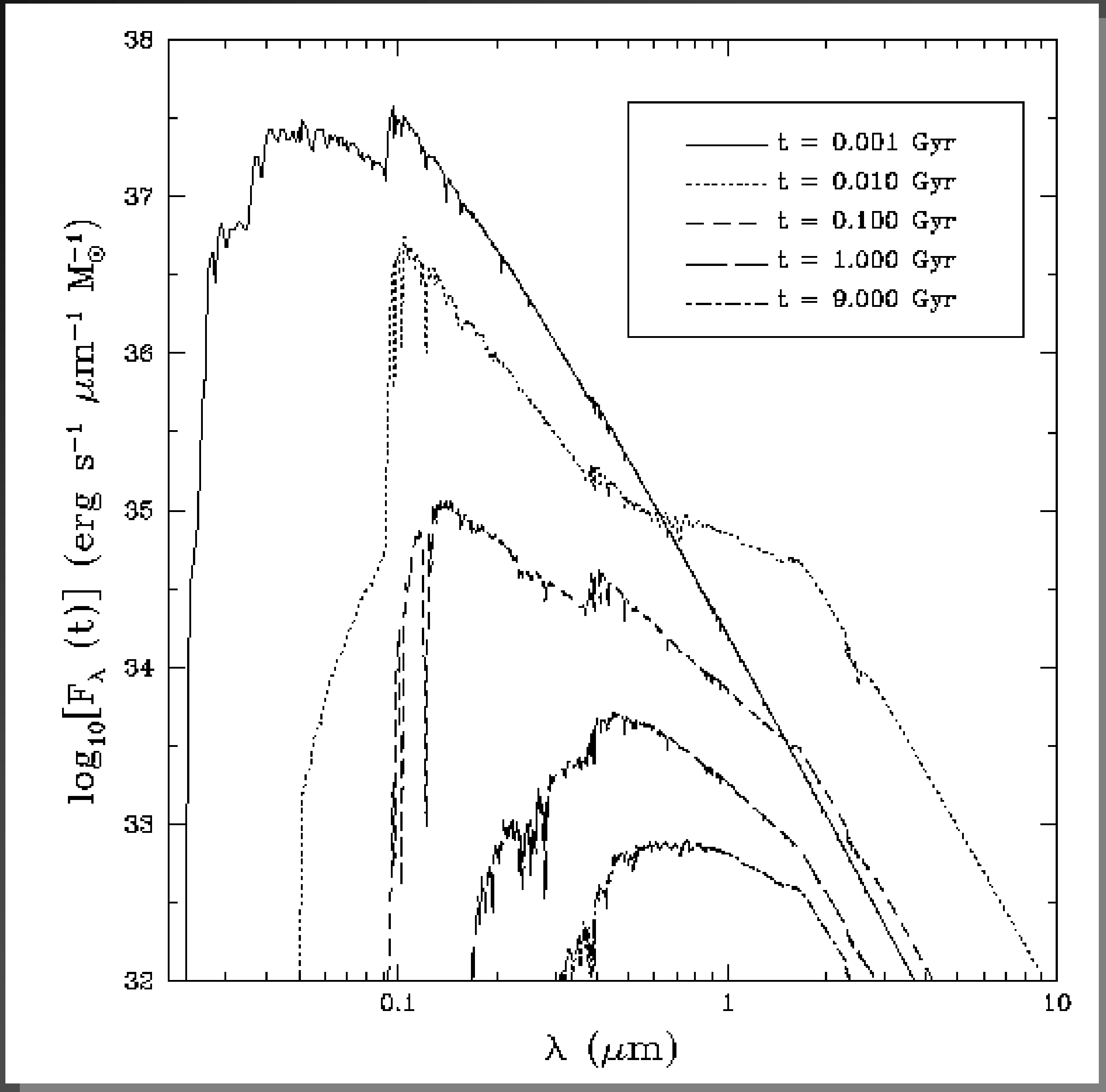
Semi-Analytic Merger Tree model



- Monte Carlo realization of halo merger history
- track H_I cooling, star formation, SN feedback, chemical evolution...
- at $z<z_{reion}$, gas collapse suppressed (Gnedin 2000, Somerville 2002)
- SF history convolved with stellar population models, dust absorption & emission

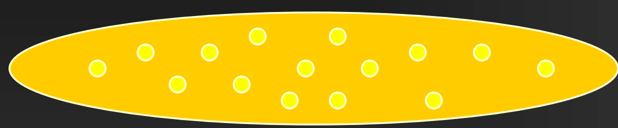
Somerville & Primack (1999)
Somerville, Primack, & Faber (2001)
collisional starburst SAM

SEDs from stellar population models



Devriendt, Guiderdoni & Sadat 1999

dust absorption and emission

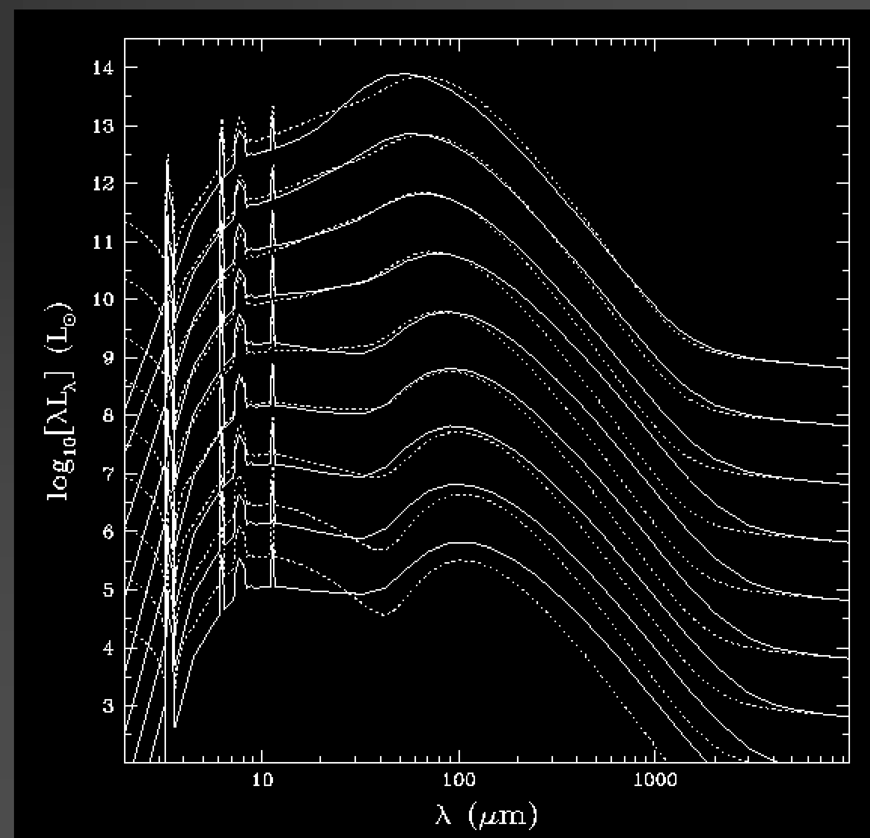


optical depth of dust proportional to column density of metals in disk

$Z_{gas}\ N_H$

energy absorbed
= energy emitted

empirical template
emission spectra
(Devriendt & Guiderdoni)
VSGs, BG, and PAHs



free parameters

- star formation efficiency α
- SN feedback efficiency β
- chemical yield y
- dust normalization τ^0_{dust}
- dust composition
- IMF

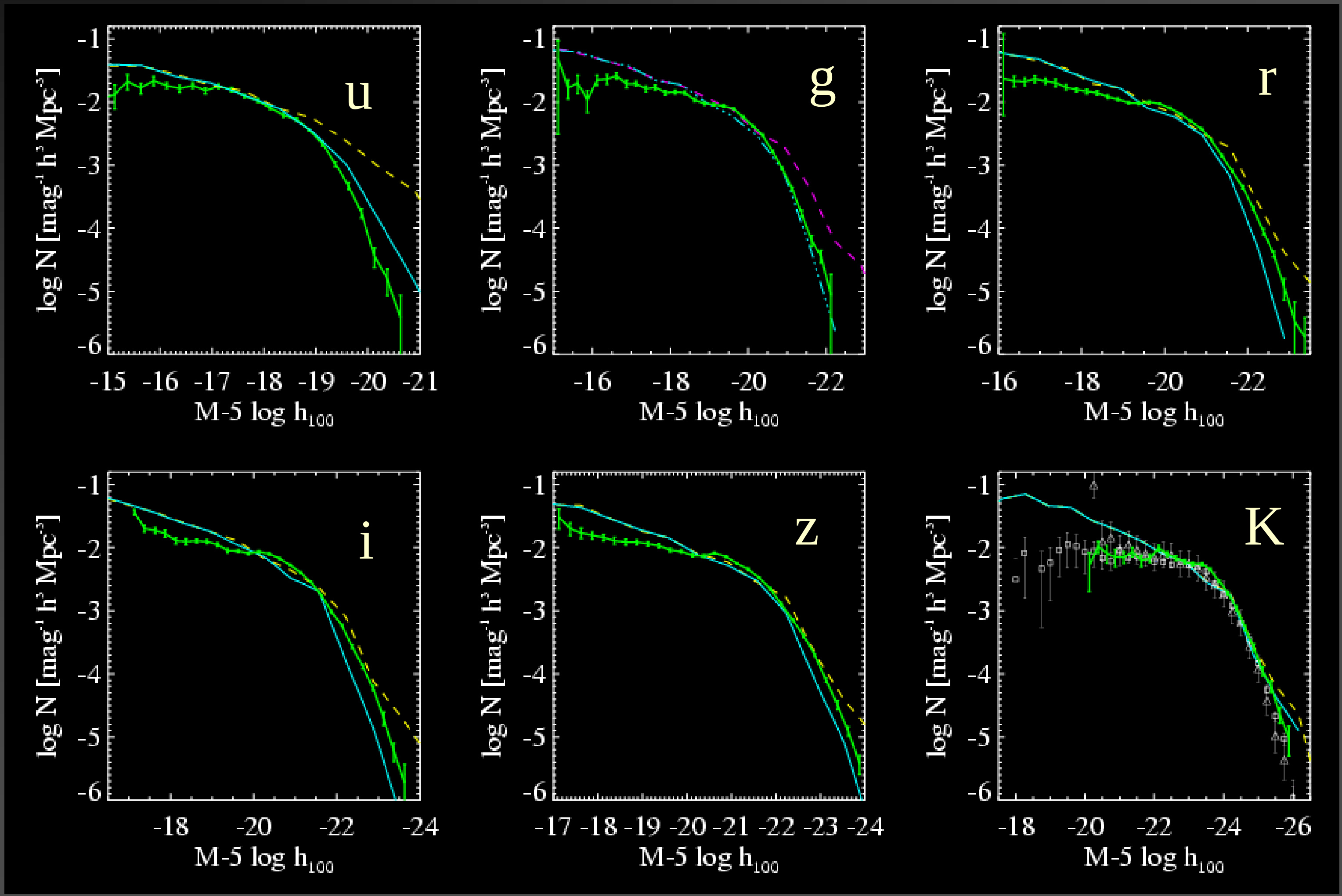
adjusted to fit a set of redshift zero observations
then left fixed

green lines
= data
(SDSS &
2MASS)

blue lines
= SAM (preliminary)
dashed lines
= SAM, no dust

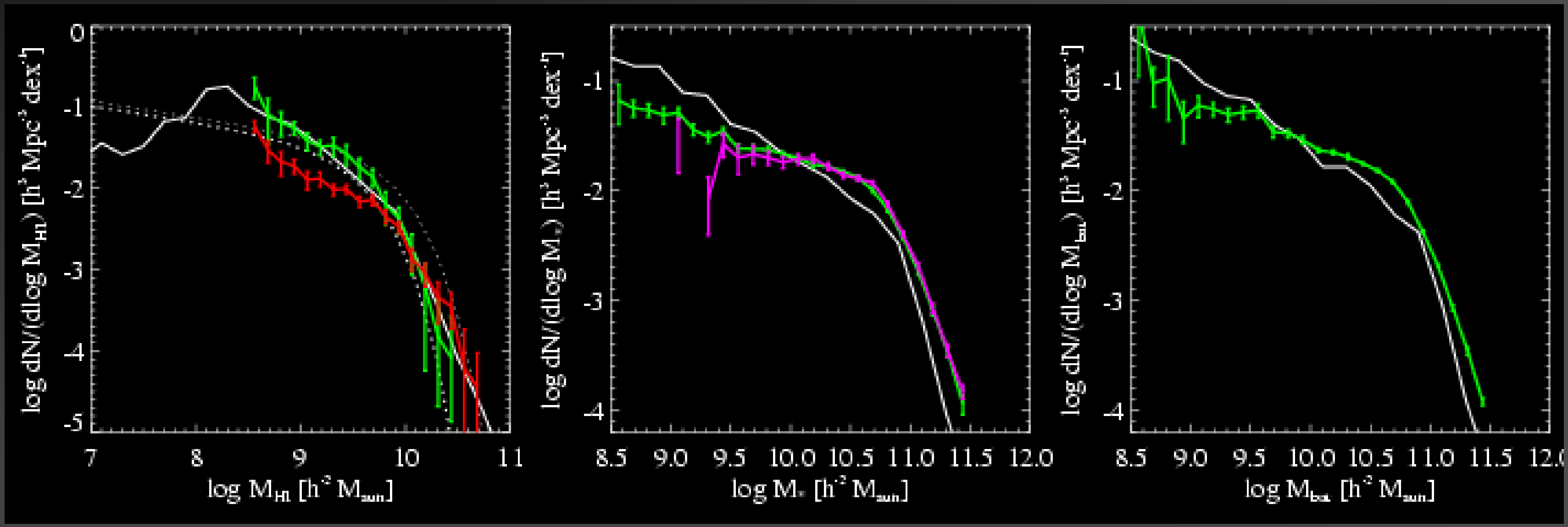
multiwavelength luminosity functions

number per unit volume



magnitude

mass functions of cold gas, stars, and baryons



cold gas mass
(HI & H_2)

stellar mass

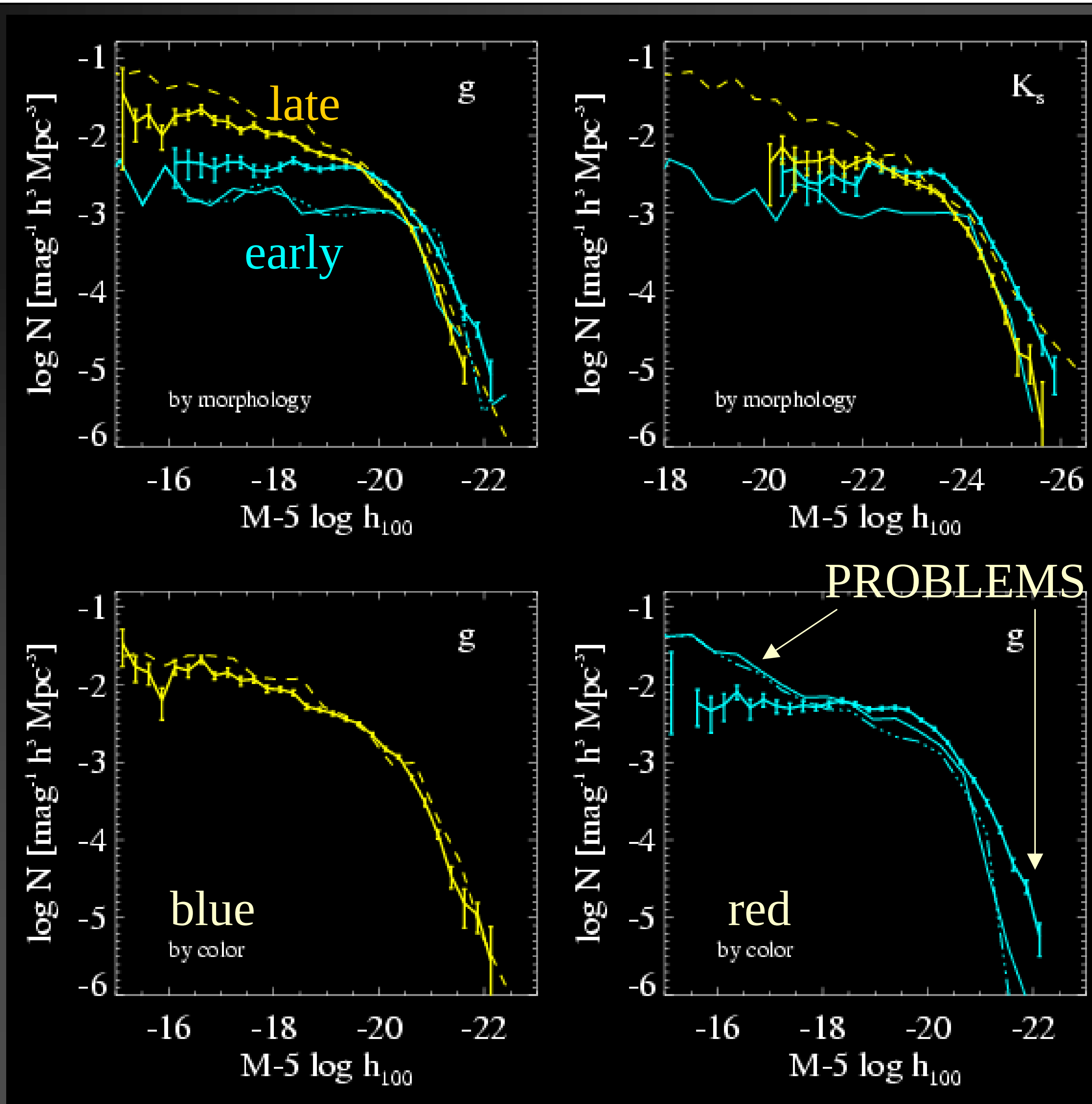
baryons

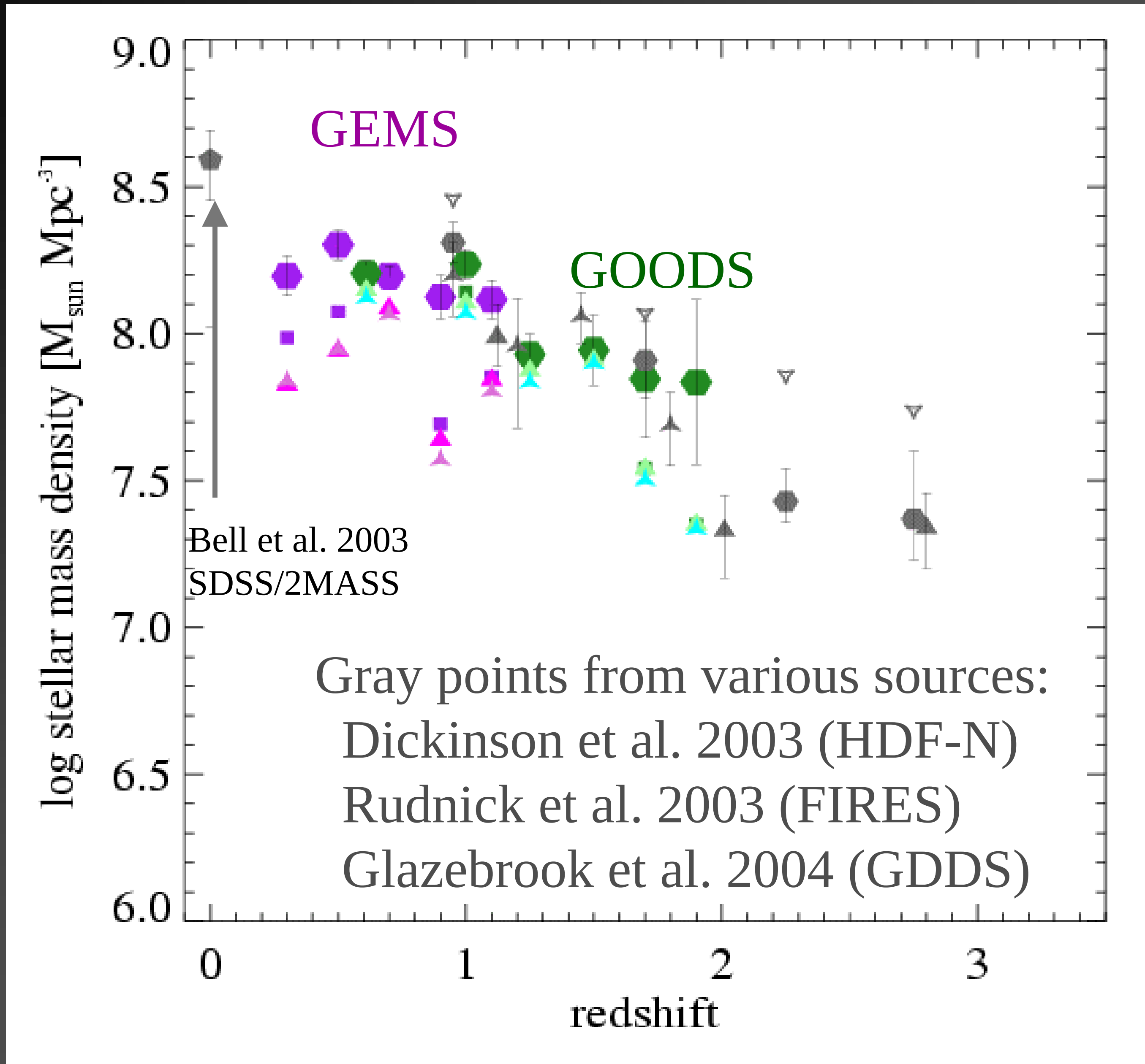
observational quantities
Bell et al. 2003

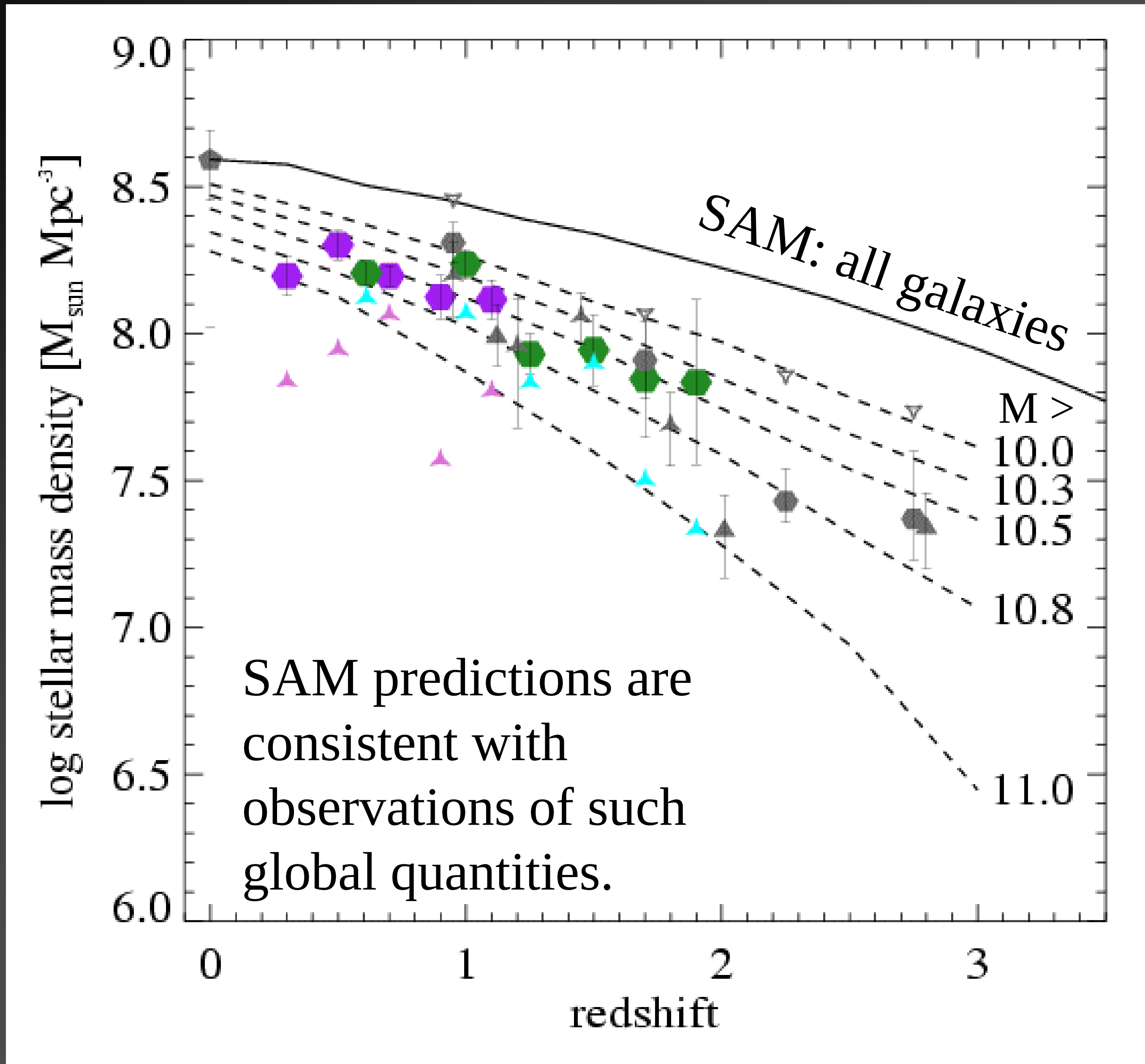
SDSS/2MASS matched sample
Bell et al. 2003

morphology
observed: concentration in r-band
model: B/T = 0.5

color:
tilted ridge in g-r

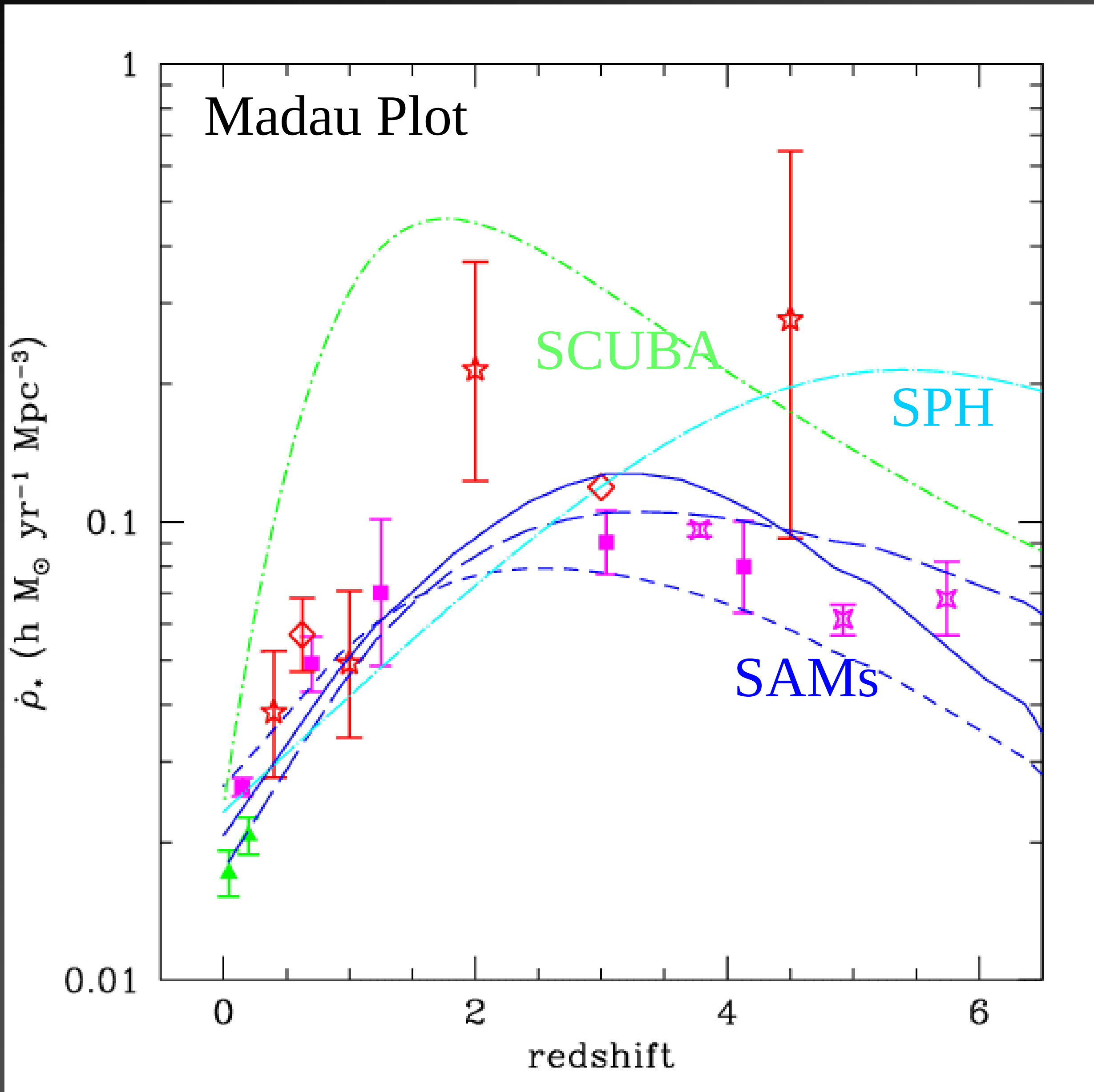



GEMS
GOODS
Bell et al. 2003
SDSS/2MASS
Gray points from various sources:
Dickinson et al. 2003 (HDF-N)
Rudnick et al. 2003 (FIRES)
Glazebrook et al. 2004 (GDDS)
log stellar mass density [M_sun Mpc^-3]
redshift
9.0
8.5
8.0
7.5
7.0
6.5
6.0
0
1
2
3



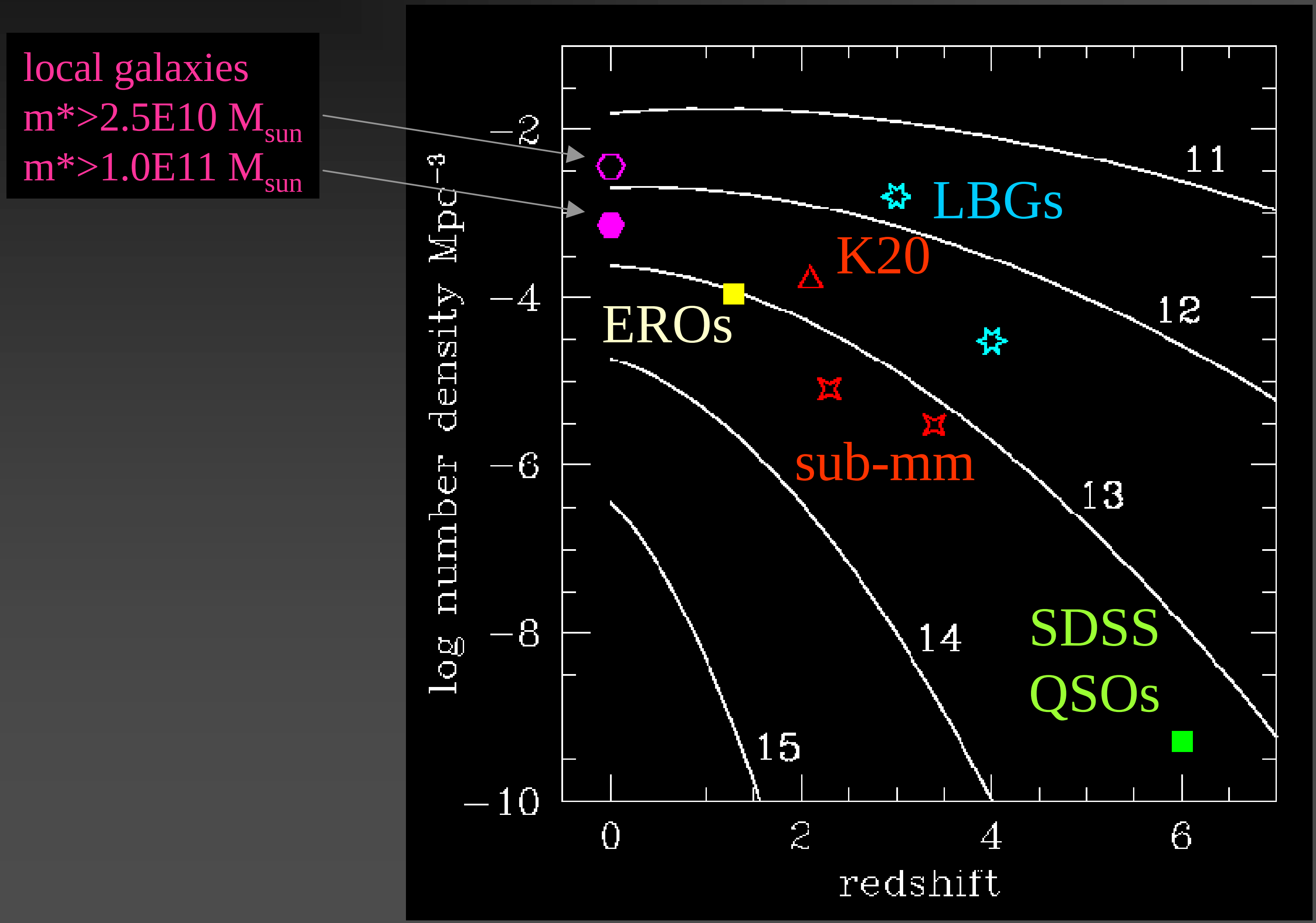
9.0
8.5
8.0
7.5
7.0
6.5
6.0
log stellar mass density [M_sun Mpc^-3]
0
1
2
3
redshift
SAM: all galaxies
M >
10.0
10.3
10.5
10.8
11.0
SAM predictions are consistent with observations of such global quantities.

the optical/IR paradox



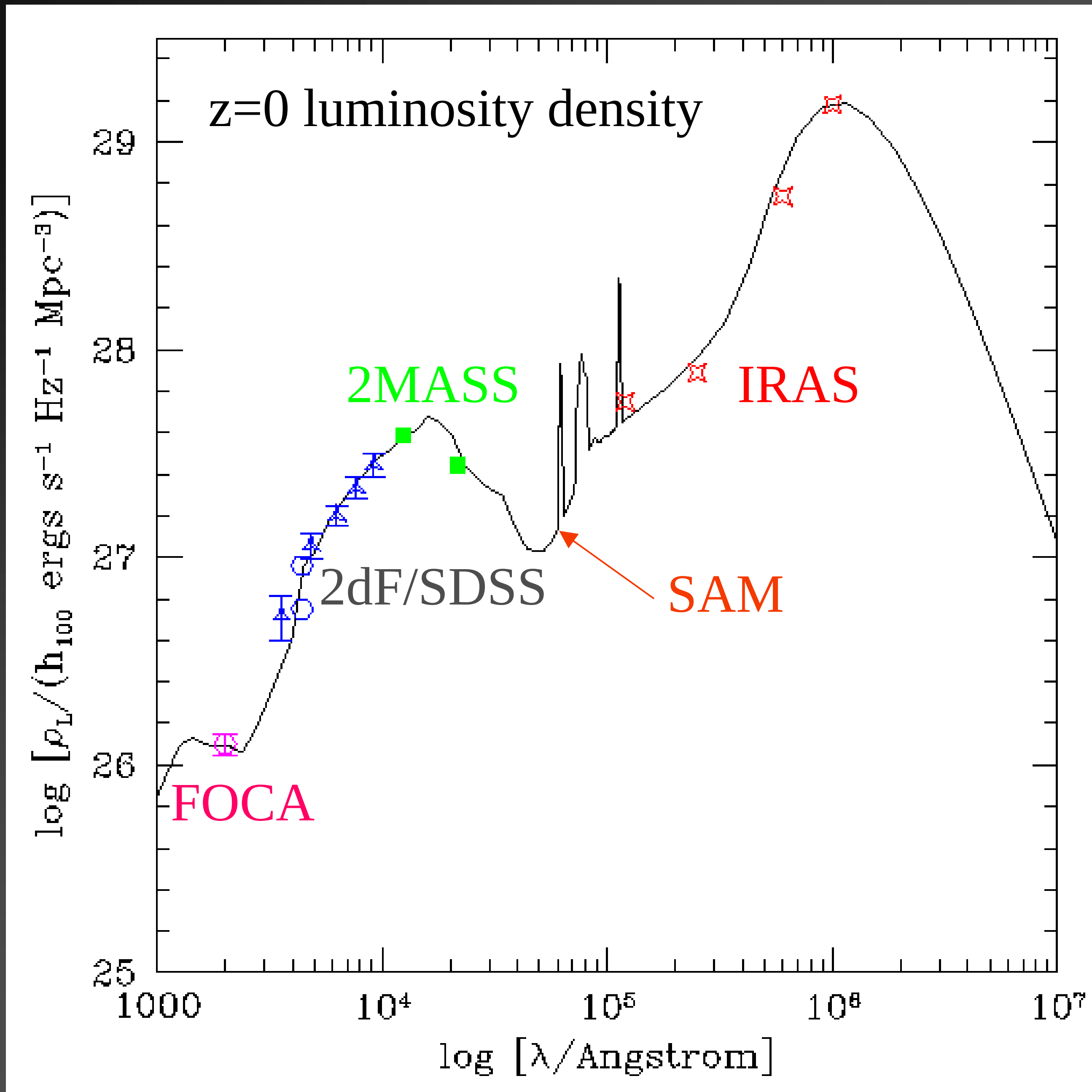
- all CDM-based models, both SAMs and the Springel-Hernquist SPH simulations, have difficulty producing enough star formation at z~2 to account for sub-mm sources & far IR background
- does the IMF depend on epoch or environment?

Do massive galaxies at high redshift pose a crisis for CDM?

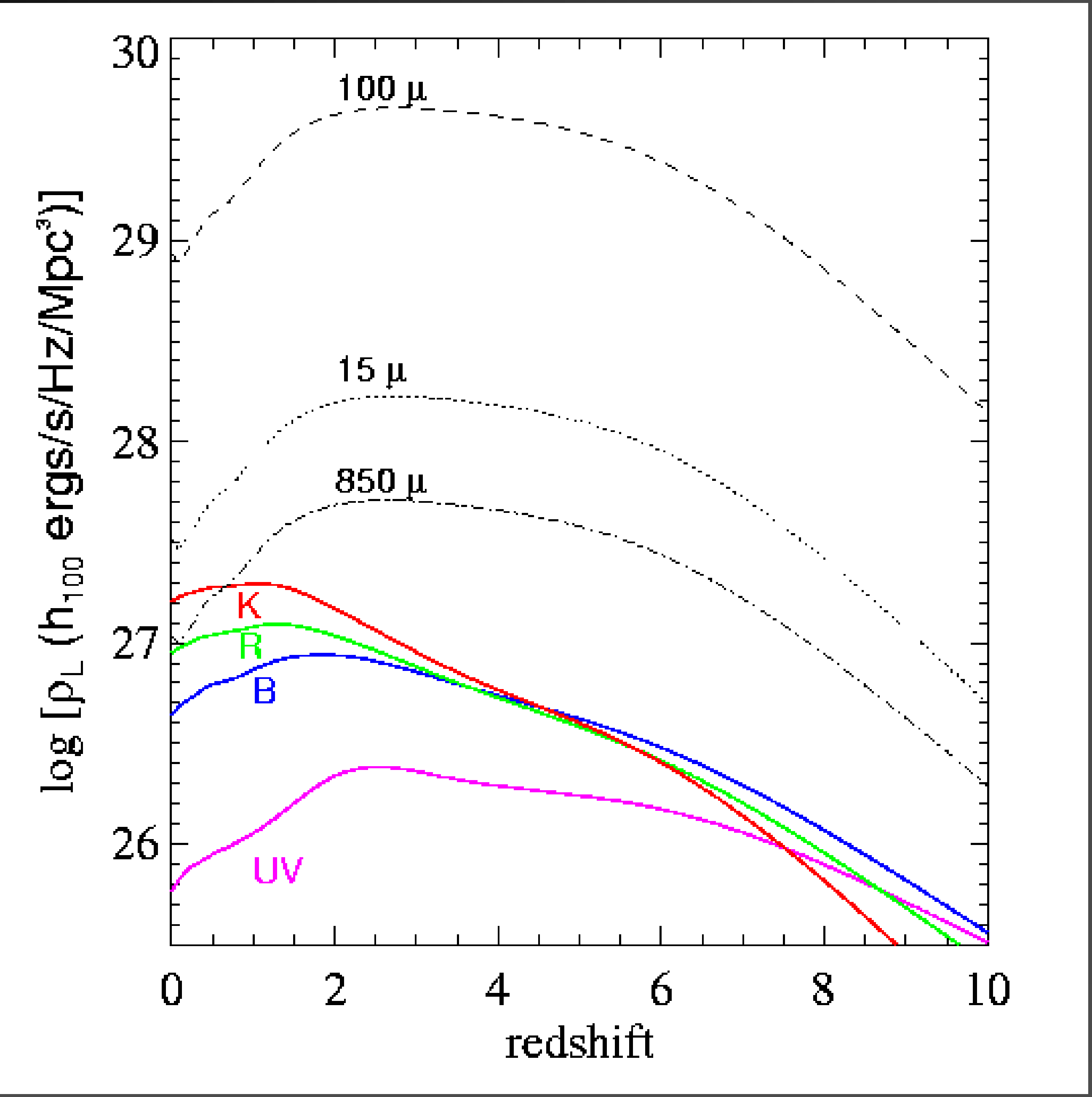


NO!

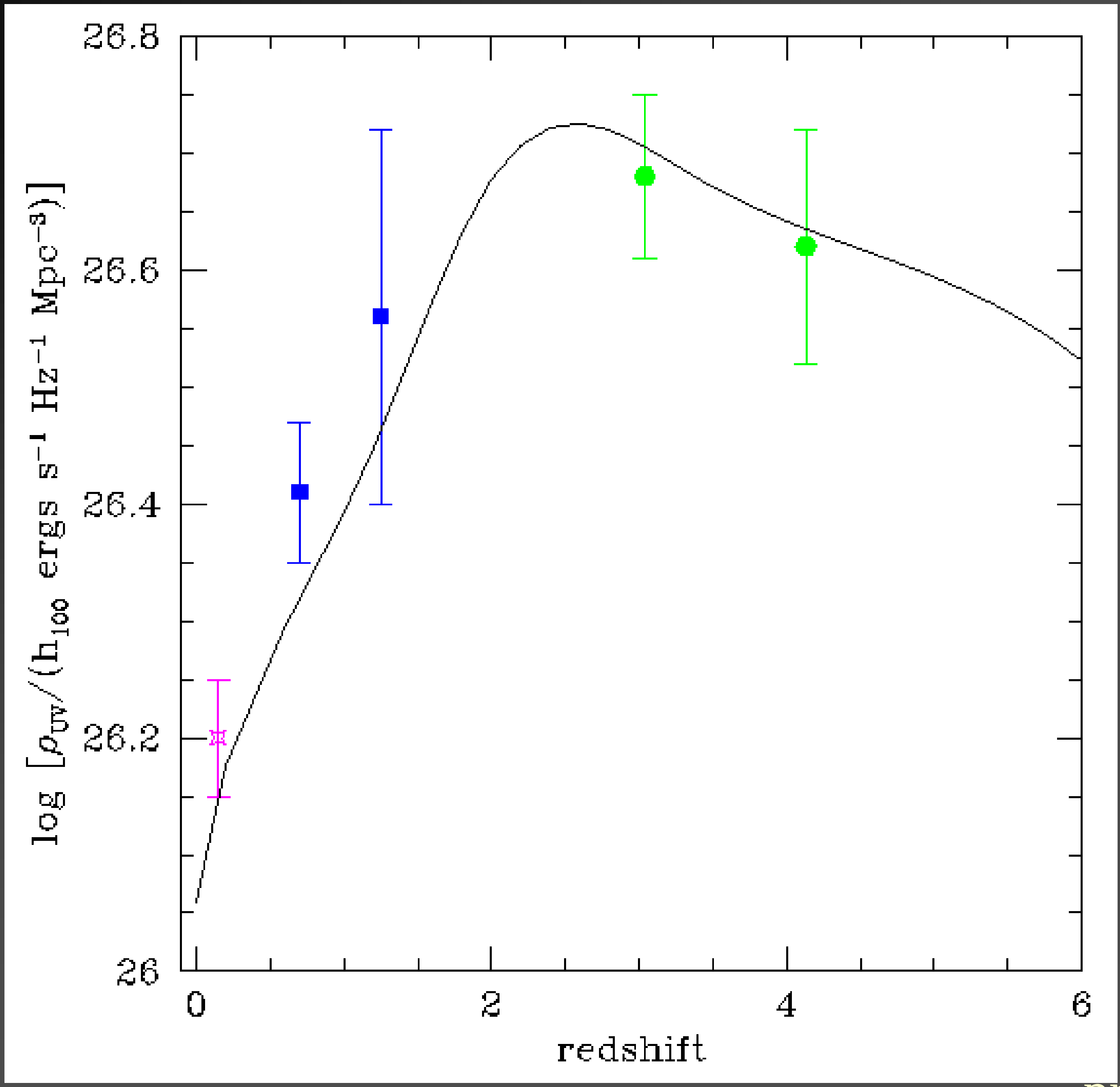
Just for star form-ation.



preliminary

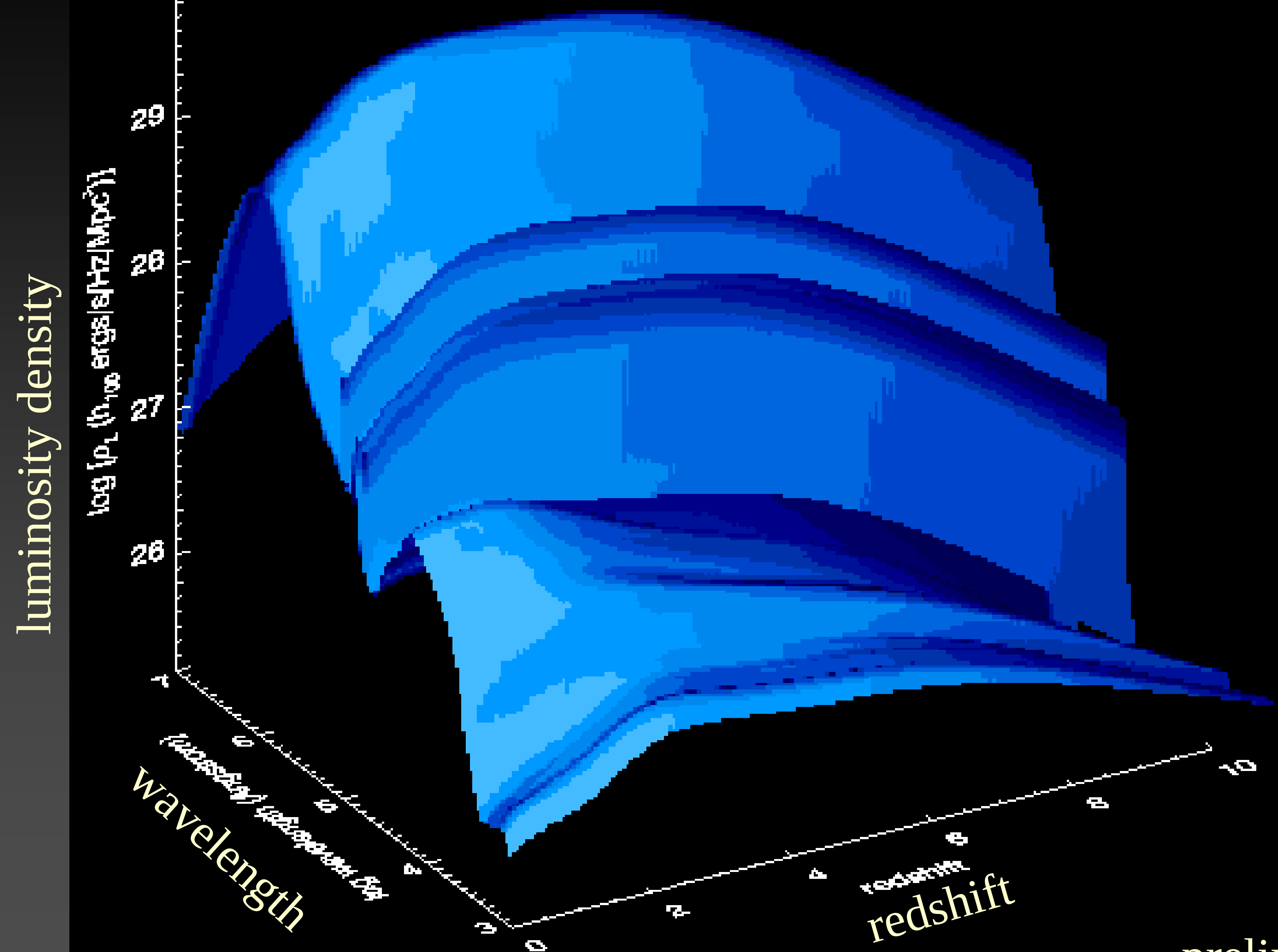


preliminary



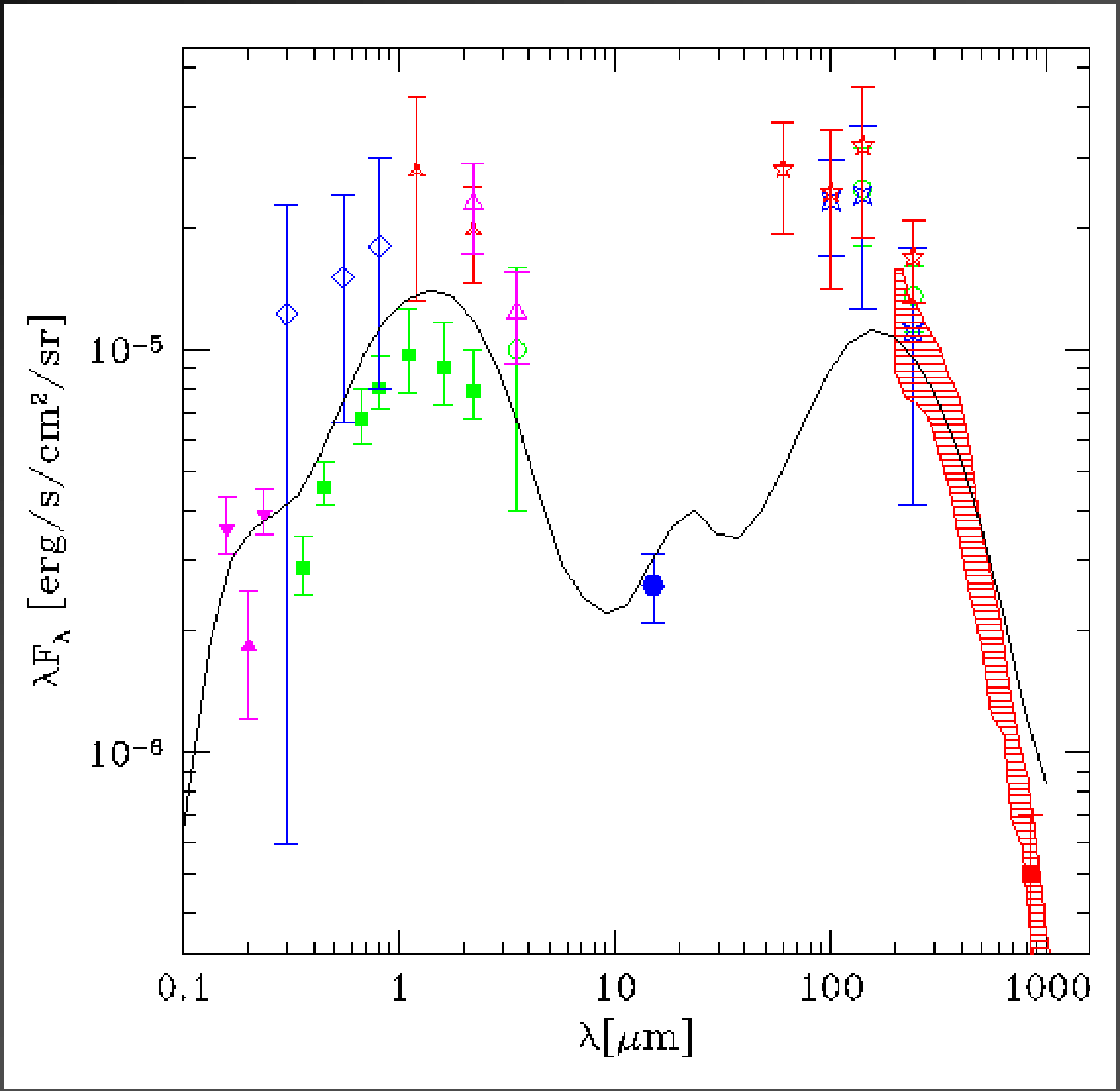
preliminary

The Bolometric Madau Diagram



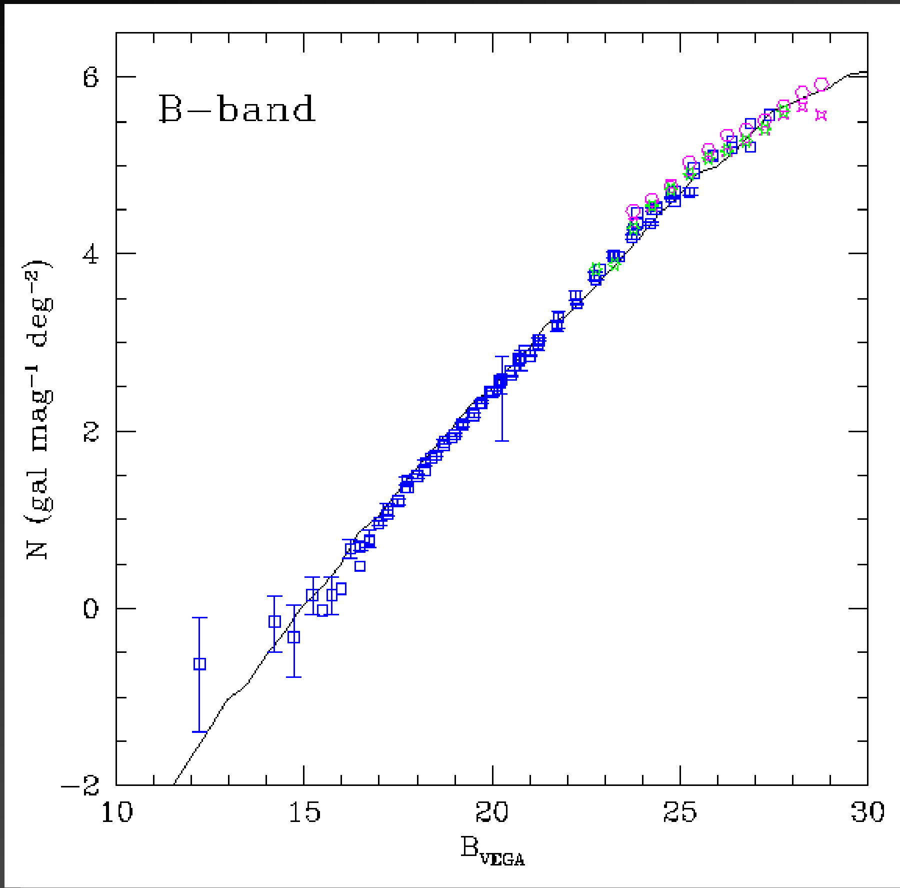
preliminary

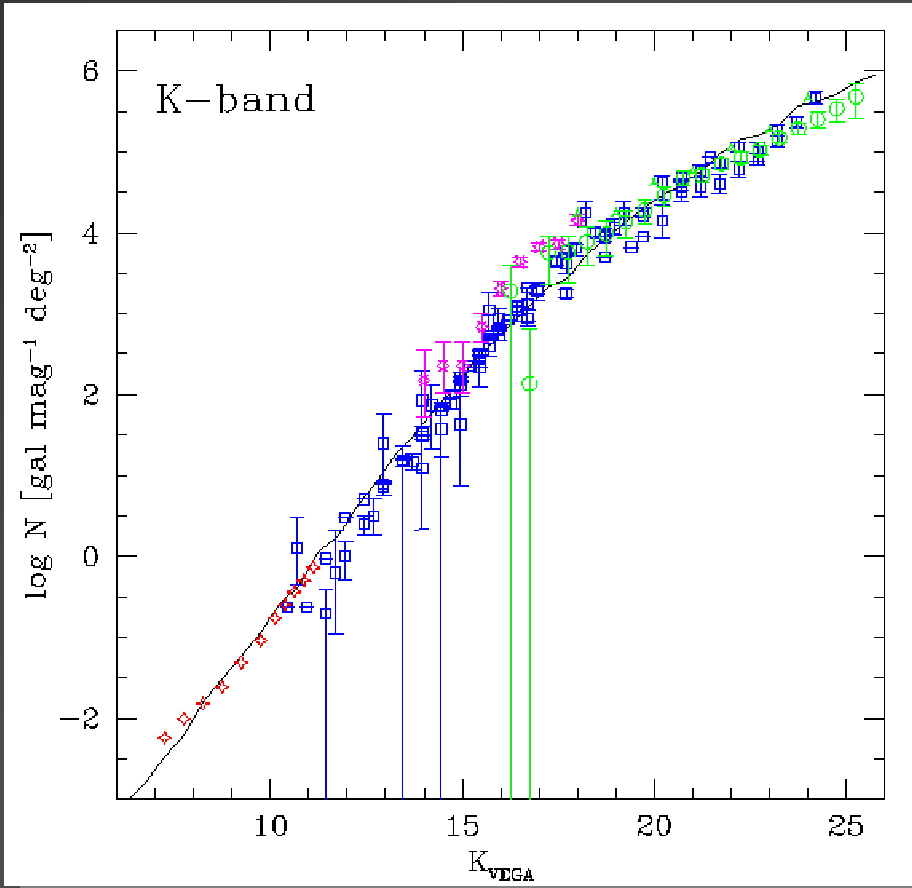
extragalactic background light

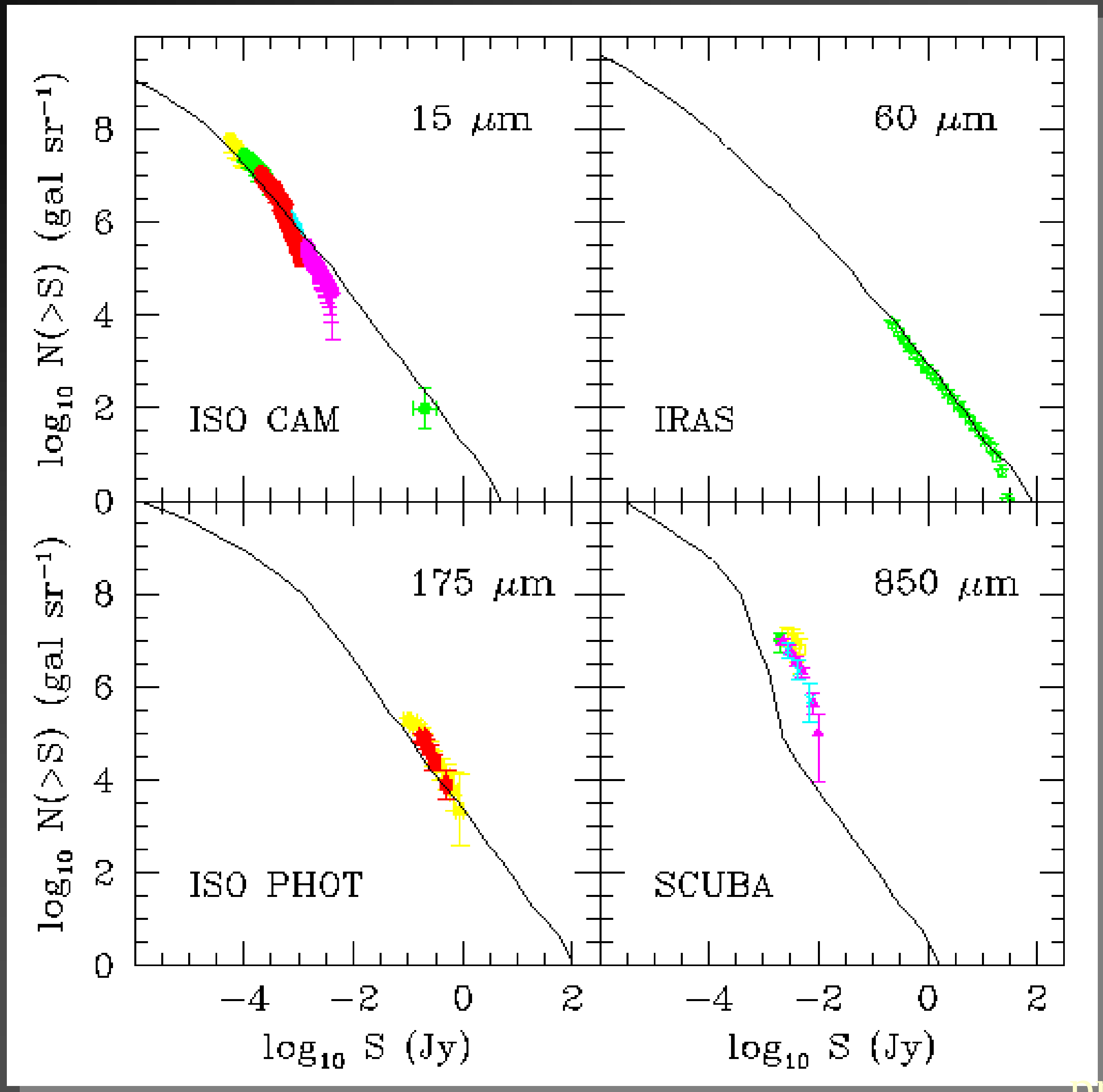


preliminary

optical/near-IR counts



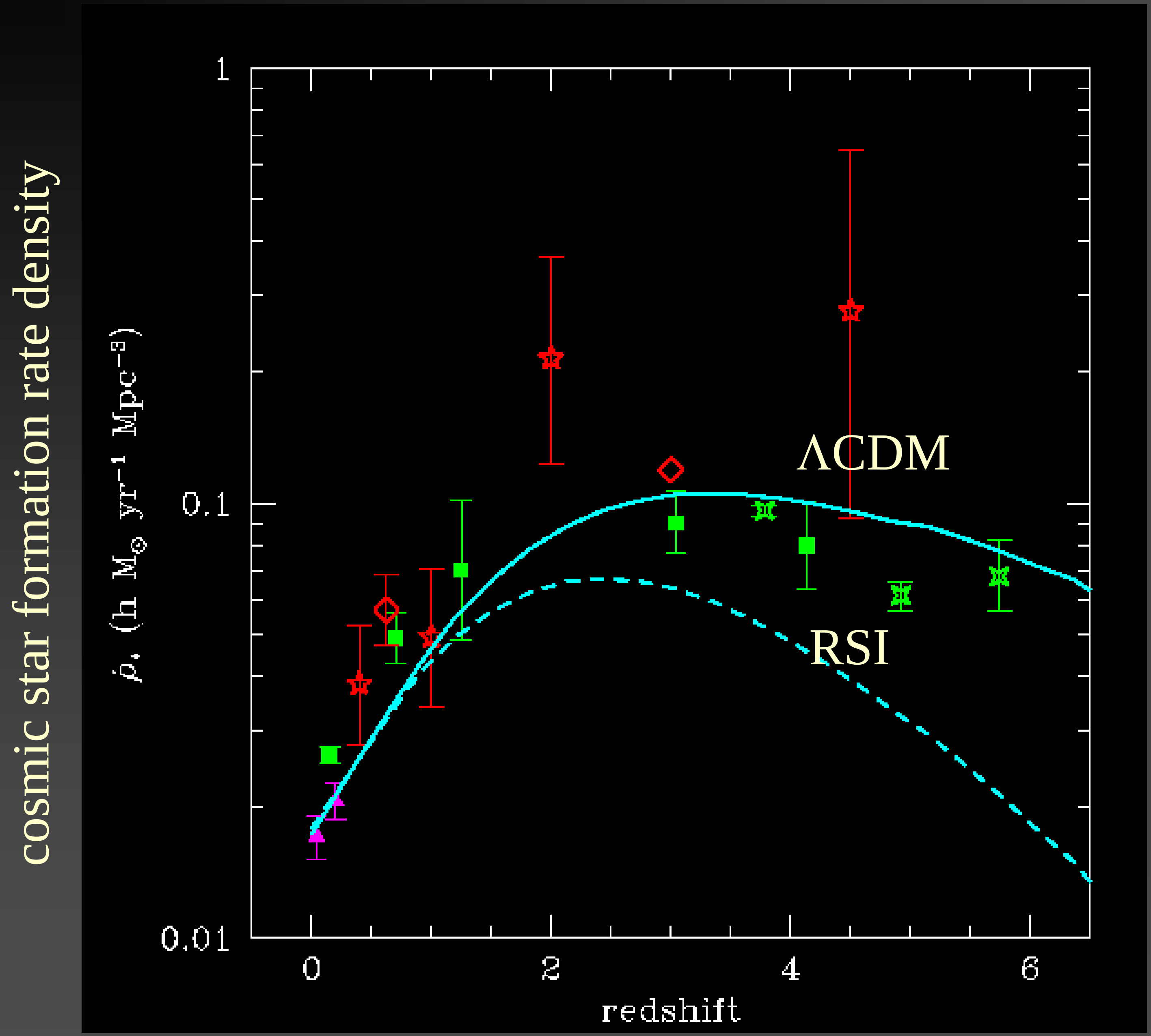



15 μm
ISO CAM
60 μm
IRAS
175 μm
ISO PHOT
850 μm
SCUBA
$\log_{10}$ N(>S) (gal sr^{-1})
$\log_{10}$ S (Jy)
preliminary

Summary of SAM-MIPS comparison at z~0.7

- optical U-V colors of real MIPS sources are all over the place; SAM MIPS sources all have blue optical U-V colors
- SAMS predict too low 24 micron flux for a fixed V mag or stellar mass; therefore IR counts too low while optical counts match data
- this is due to two problems: not enough high mass, high SFR galaxies, AND fraction of light absorbed by dust underpredicted for high SFR (though agrees well w/ data at low SFR).

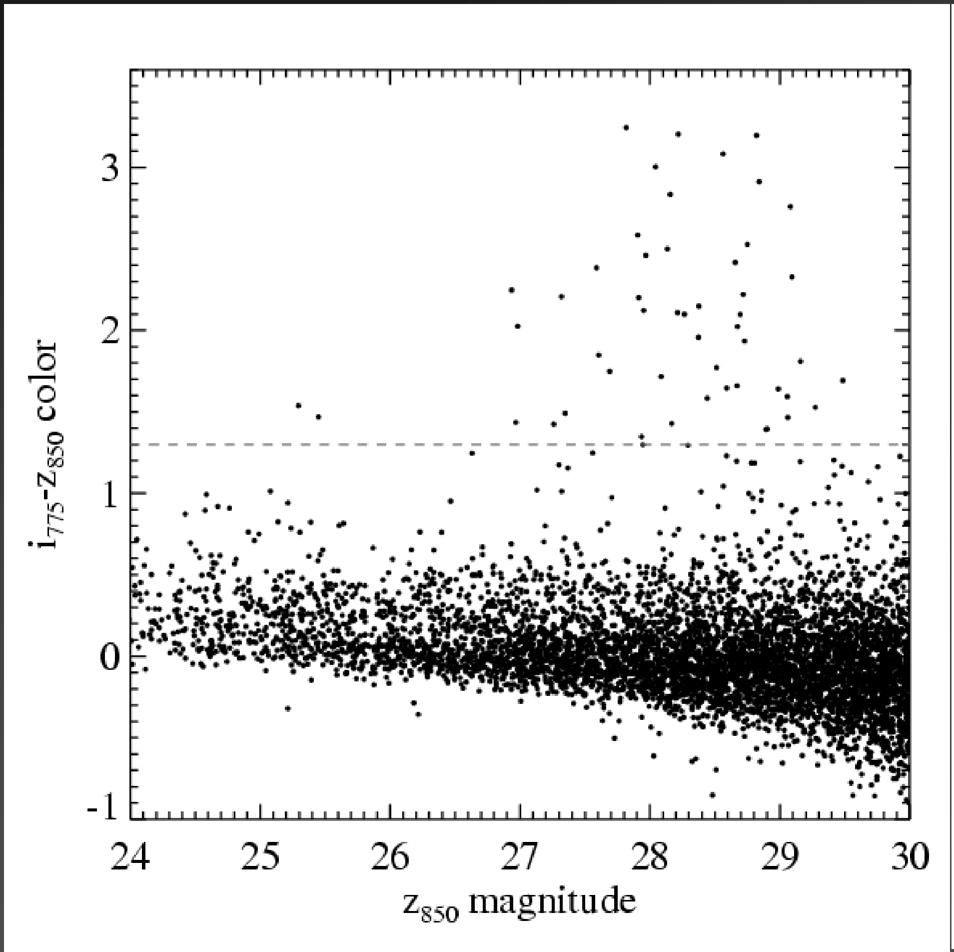
very high redshift galaxies ($z>5$)



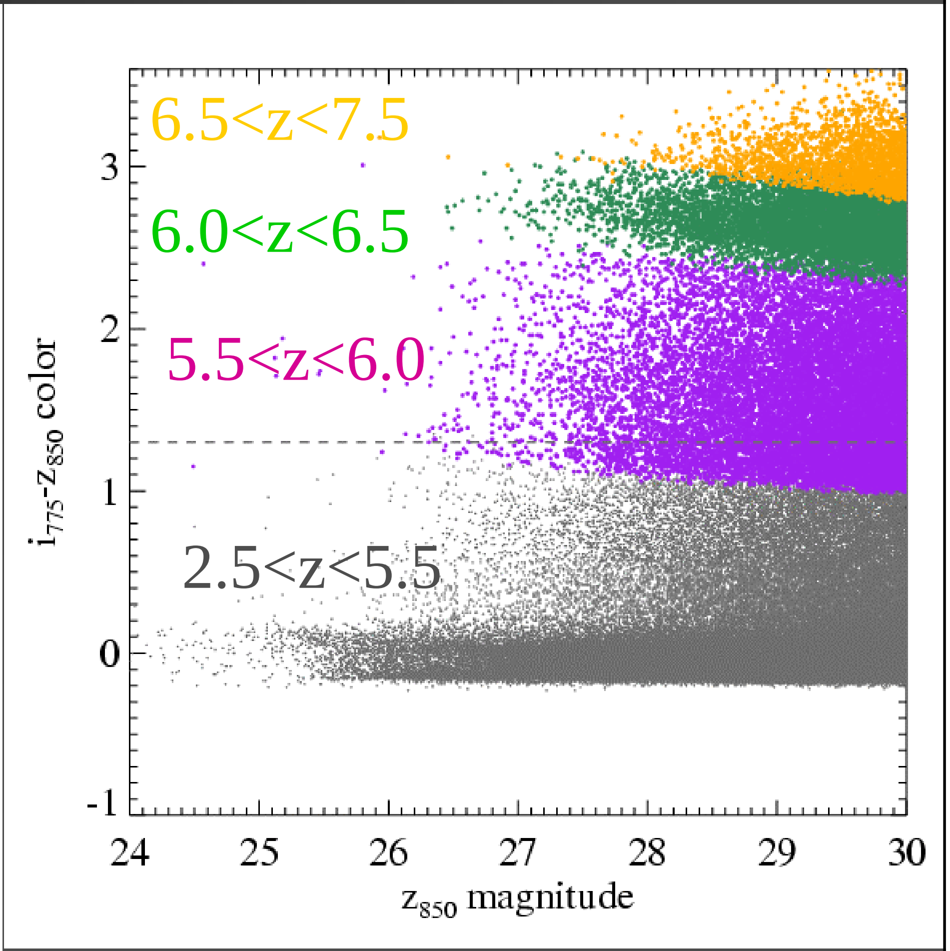
The SFR at high z depends on the primordial power spectrum – we assume no-tilt ΛCDM rather than Running Scale Index (RSI)

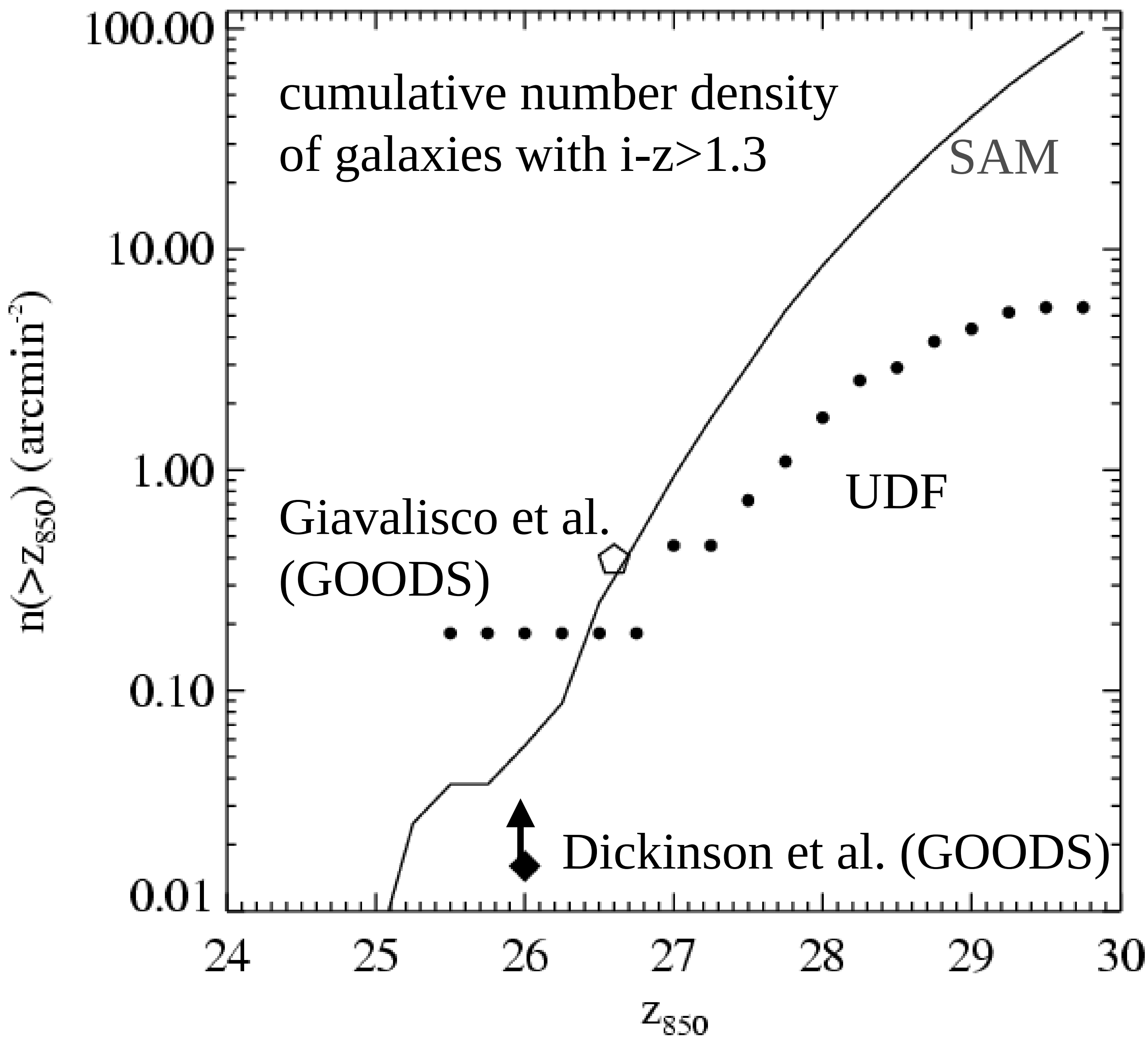
Somerville in prep

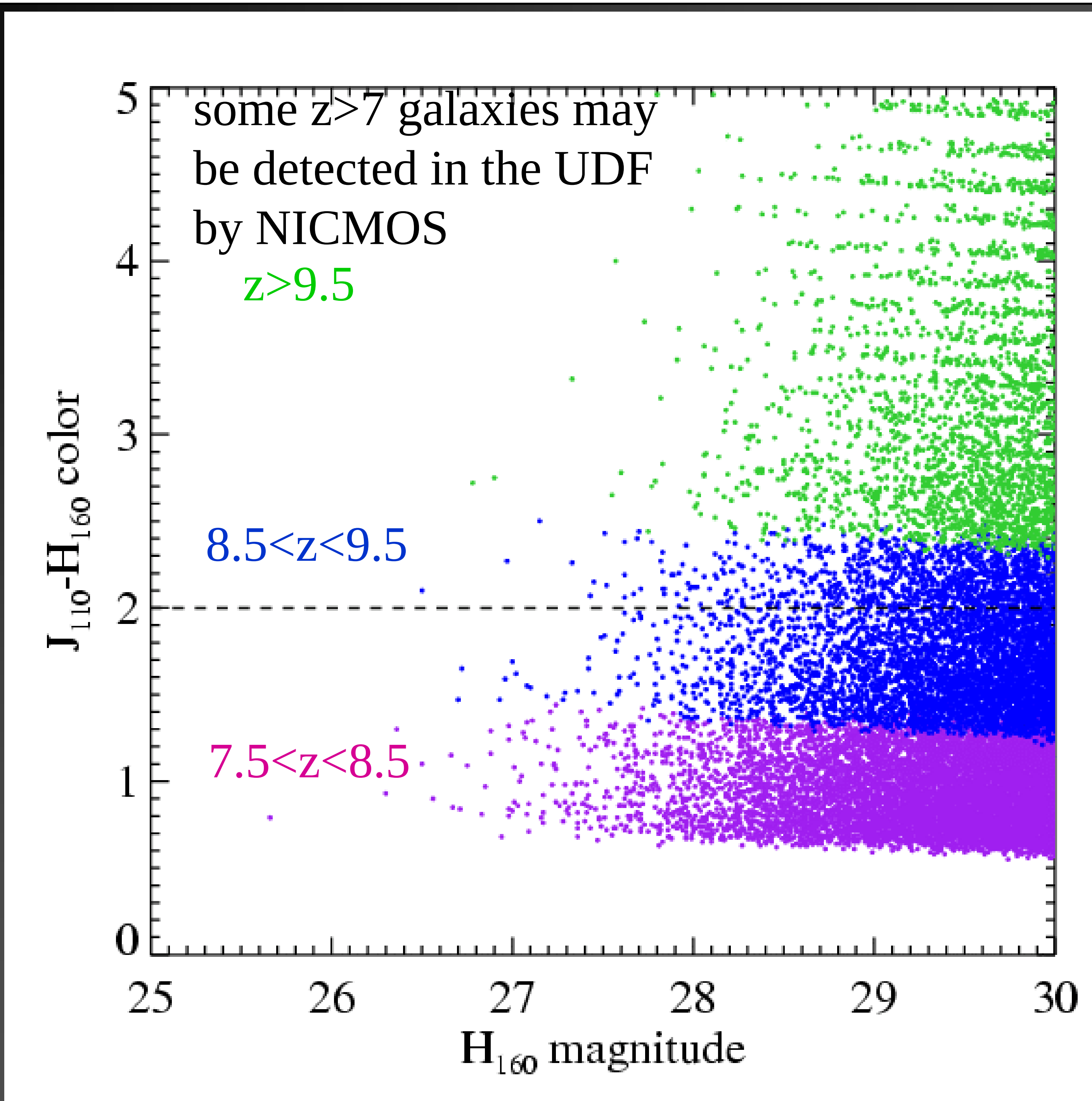
The real UDF



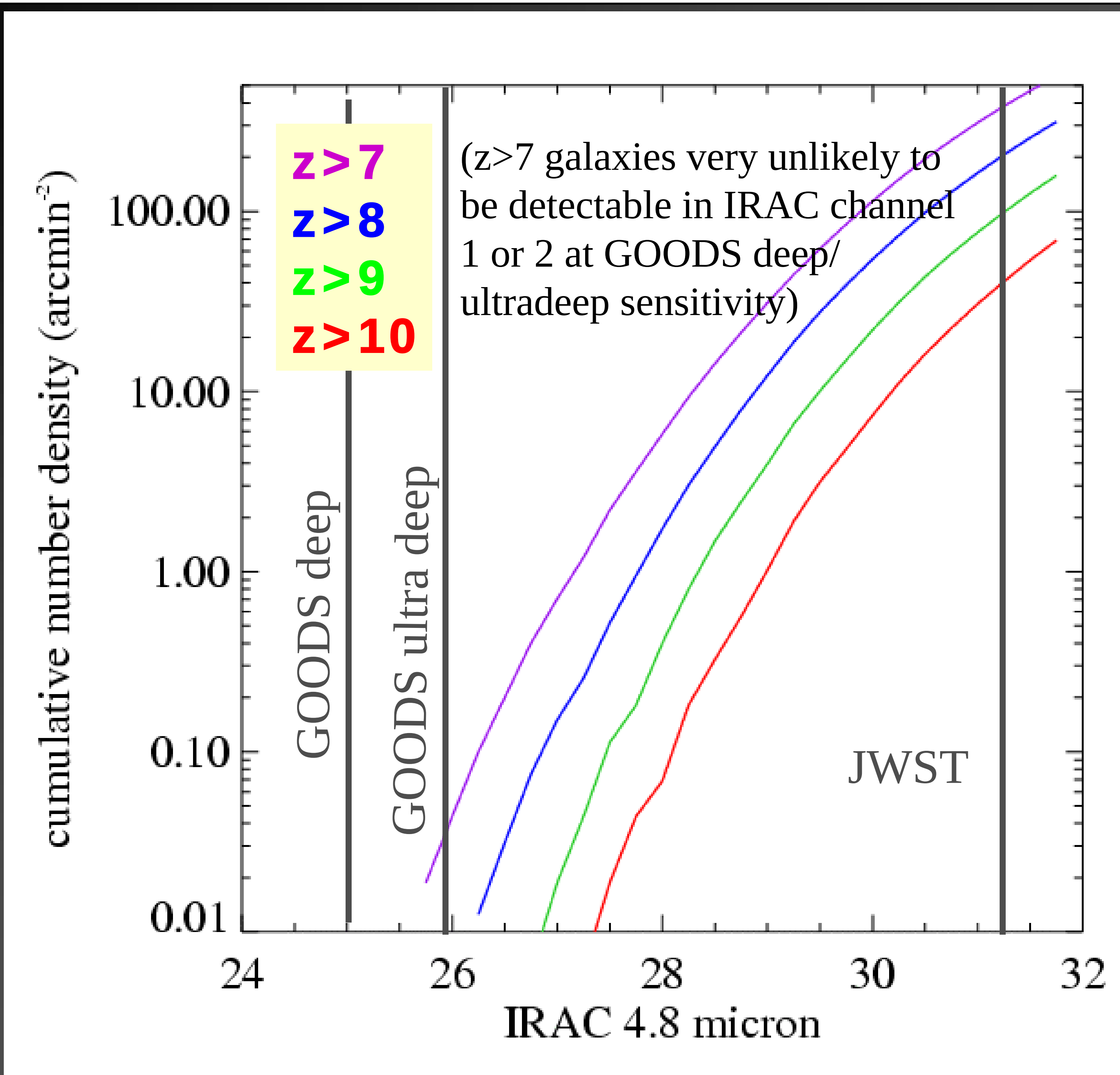
SAM mock catalog (area of GOODS to depth of UDF)




cumulative number density
of galaxies with i-z>1.3
SAM
UDF
Giavalisco et al.
(GOODS)
Dickinson et al. (GOODS)
100.00
10.00
1.00
0.10
0.01
n(>z850) (arcmin-2)
24
25
26
27
28
29
30
z850



some z>7 galaxies may be detected in the UDF by NICMOS
z>9.5
8.5<z<9.5
7.5<z<8.5
J_{110}-H_{160} color
H_{160} magnitude
0
1
2
3
4
5
25
26
27
28
29
30



z>7
z>8
z>9
z>10
(z>7 galaxies very unlikely to be detectable in IRAC channel 1 or 2 at GOODS deep/ ultradeep sensitivity)
GOODS deep
GOODS ultra deep
JWST
cumulative number density (arcmin^{-2})
100.00
10.00
1.00
0.10
0.01
24
26
28
30
32
IRAC 4.8 micron

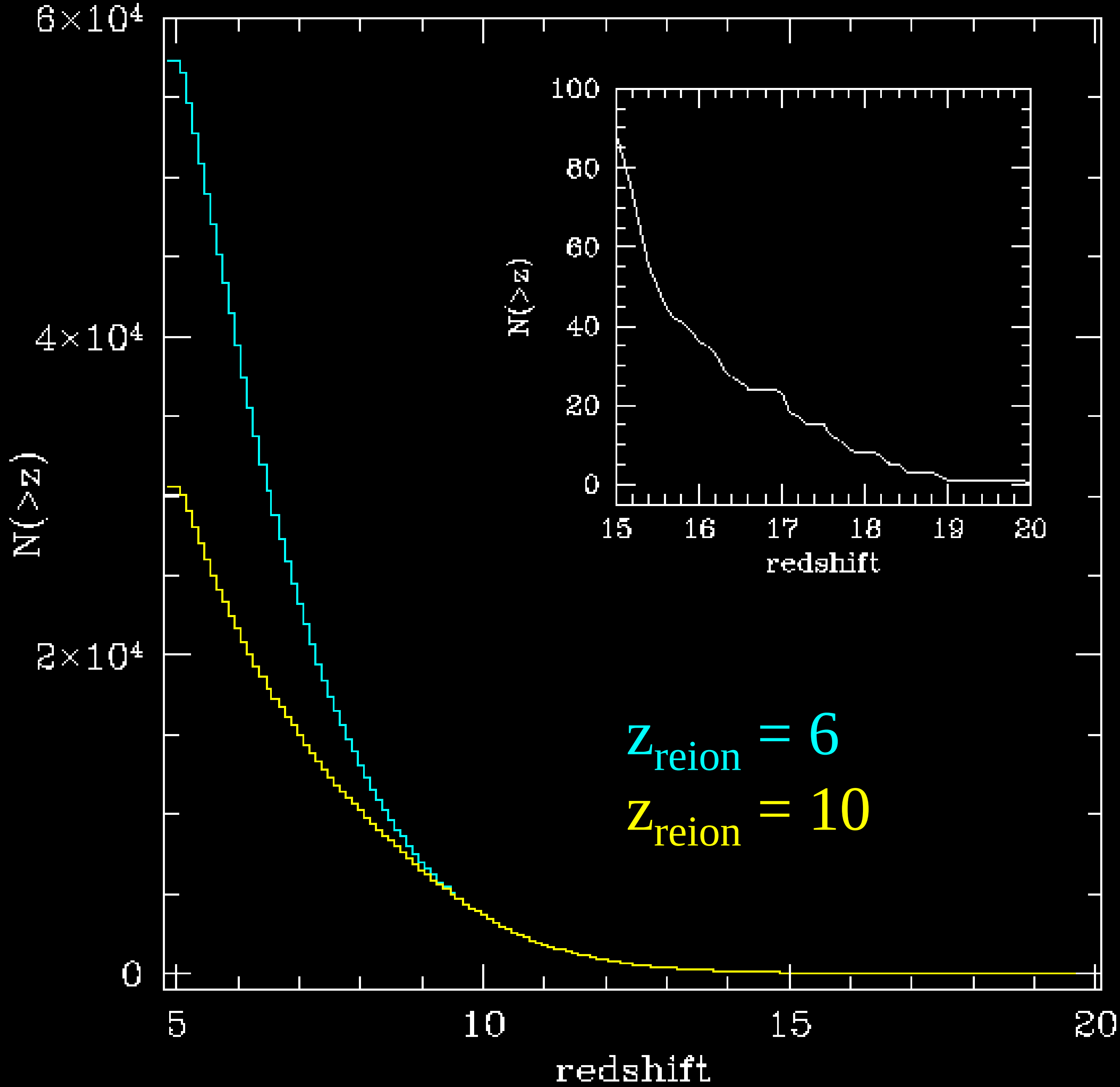
cumulative
redshift
distribution

(5x5) $arcmin^2$

flux-limited at

1 nJy

(m_{AB} < 31.4)



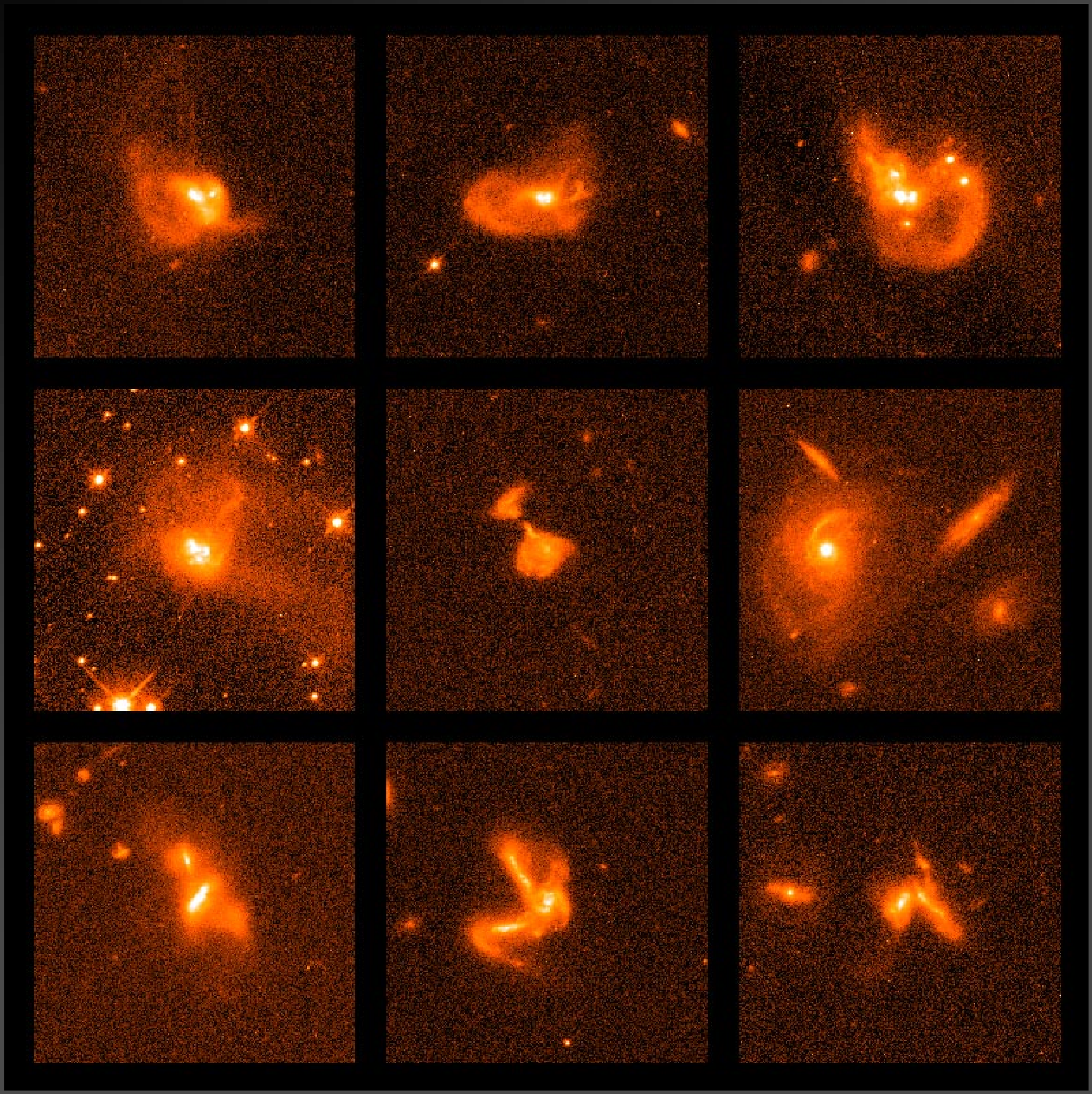
Summary:

- if we are lucky, we may pick up a handful of $z>7$ galaxies with HST/Spitzer or via tricks like lensing
- models predict and Spitzer data support: galaxies at $z\sim6$ are relatively evolved creatures – they are not experiencing their first star formation episode!
- models predict large populations of galaxies at $z=7$-20 will be detected by JWST...but these objects will be tiny...need higher spatial resolution than JWST?

Predictions from Galaxy Modeling:

Hydrodynamic Simulations of Interacting Galaxies

Collaborators: T J Cox & P Jonsson



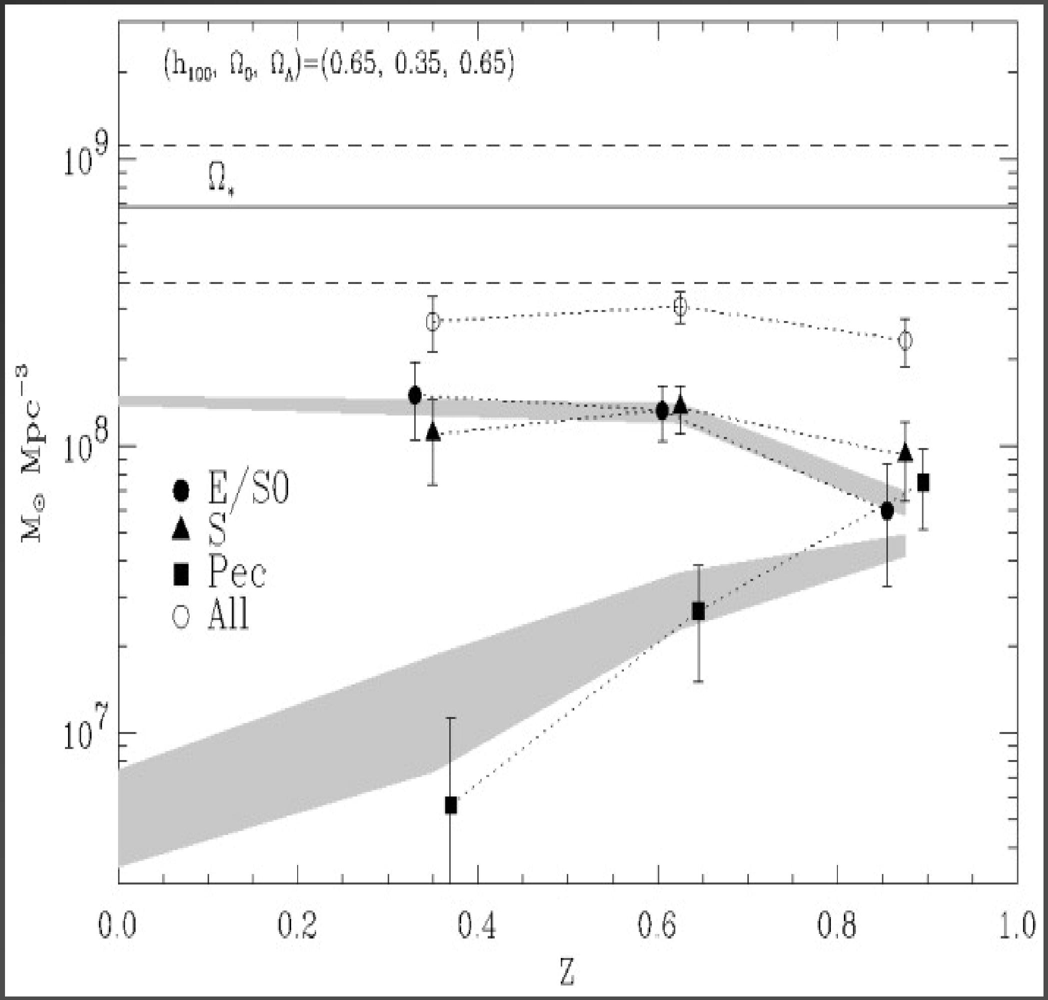
Ultra-Luminous IR Galaxies (ULIRGs) are the most prodigious star forming (>100 $M_\odot$/yr) galaxies in the local universe.

Many (arguably all) show signs of multiple nuclei, tidal features, or are visibly several galaxies involved in a “train wreck”!

Borne et al. (2000)

Merger Fraction Increases to z~1

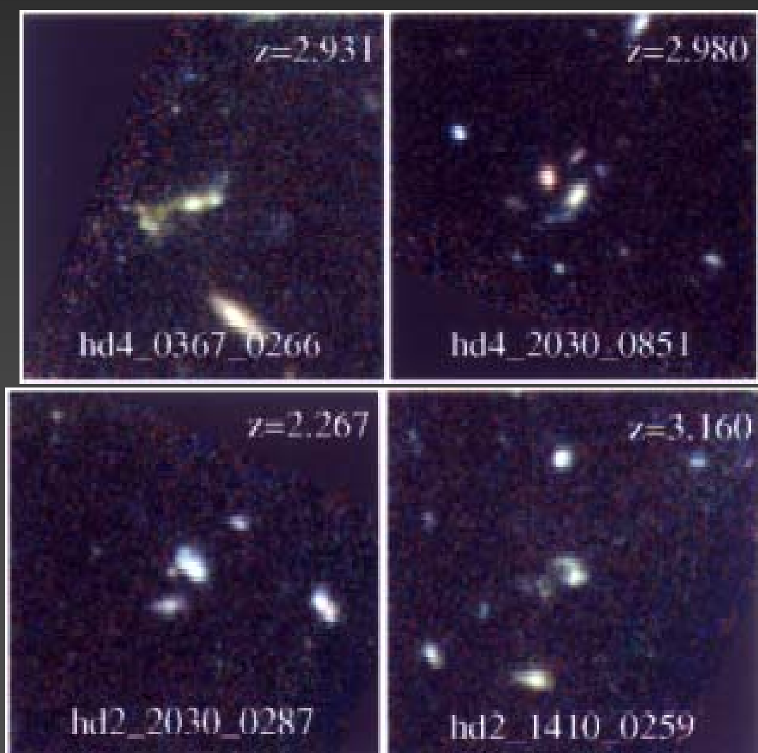
Brinchmann & Ellis (2000) studied galaxy morphology in the Hubble Deep Field (HDF) and found a distinct rise in the number density of peculiar (read: interacting?) galaxies as a function of redshift.



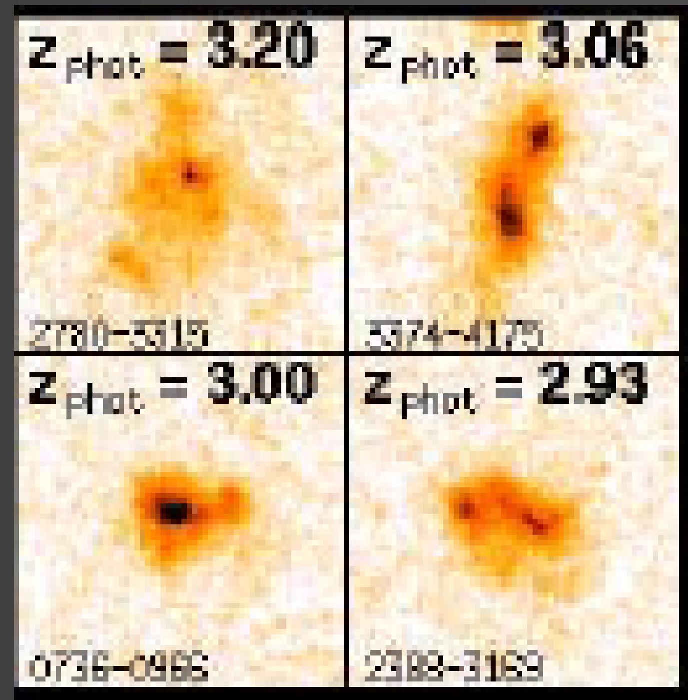
- Consistent with Patton et al. (2002) measurement of the merger rate, as measured by close pairs of galaxies, in the CNOC2 survey.

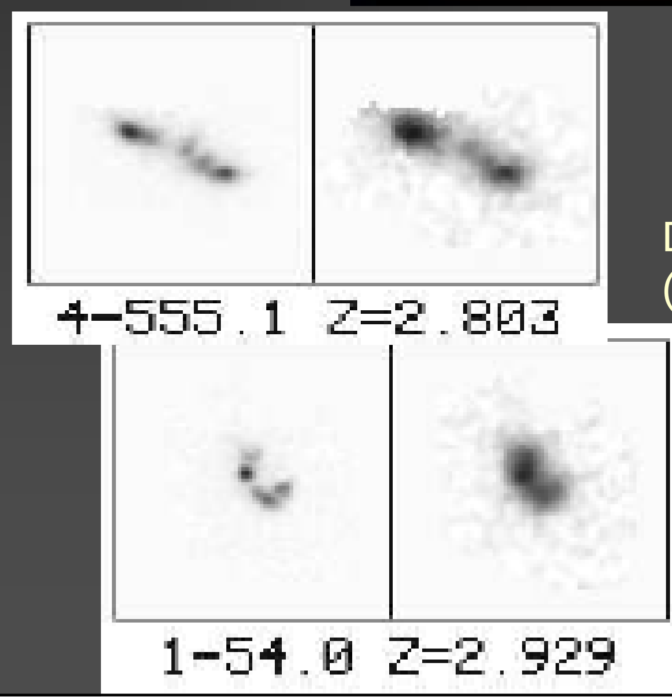
Lyman Break Galaxies (LBGs) show significant signs of disturbed (merger?) morphology

Lowenthal et al. (1997)

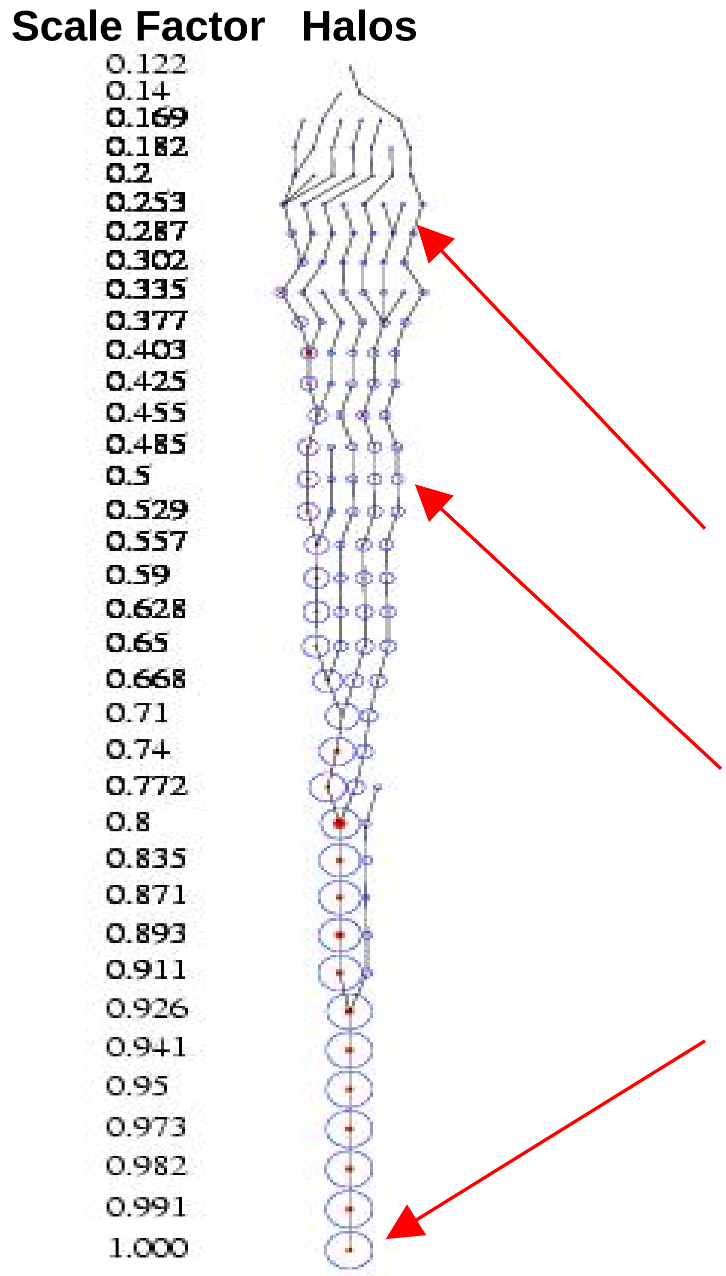


Moller et al. (2002)





Dickinson (2000)



Wechsler et al. 2002

Theory: ΛCDM Cosmology

Within the currently favored cosmology (LCDM), structure forms hierarchically. Dark matter halos (and possibly the galaxies they host) are built by a series of discrete merging events.

- ***Z=3***

  Major progenitor: 3.9 x 10^{11} $M_\odot$

  12 distinct halos (> 2.2 x 10^{10} $M_\odot$)

- ***Z=1***

  Major progenitor: 1.5 x 10^{12} $M_\odot$

  6 distinct halos (> 2.2 x 10^{10} $M_\odot$)

- ***Z=0***

  1 Galaxy size halo roughly the size of the Milky Way, Mass=2.9 x 10^{12} $M_\odot$

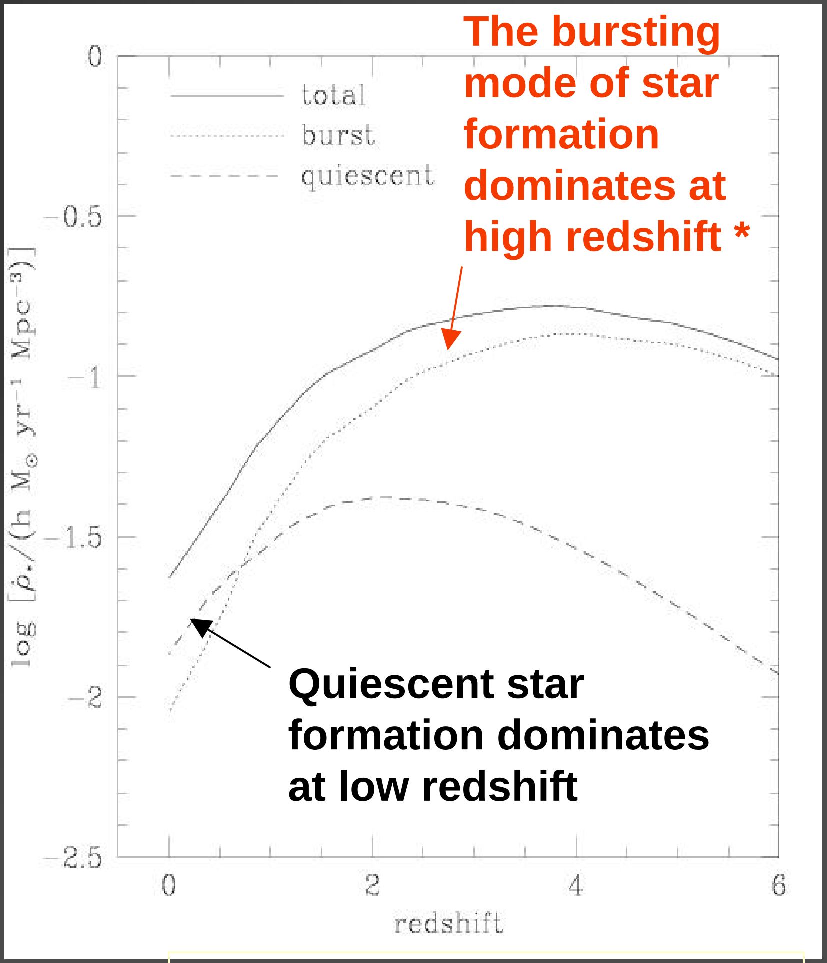
Cosmological Semi-Analytic Models (SAMs)

Feeding parameterized starbursts into semi-analytic models for galaxy formation Somerville, Primack & Faber (2001) found this model (as opposed to models without collisional starbursts) better fit data for:

1) Co- moving number density of galaxies at z>2

2) Luminosity function at z=3 (and more recently up to z=5)

* The majority of stars were generated by star formation induced by galaxy mergers



Careful: this is redshift not time!

Our Work

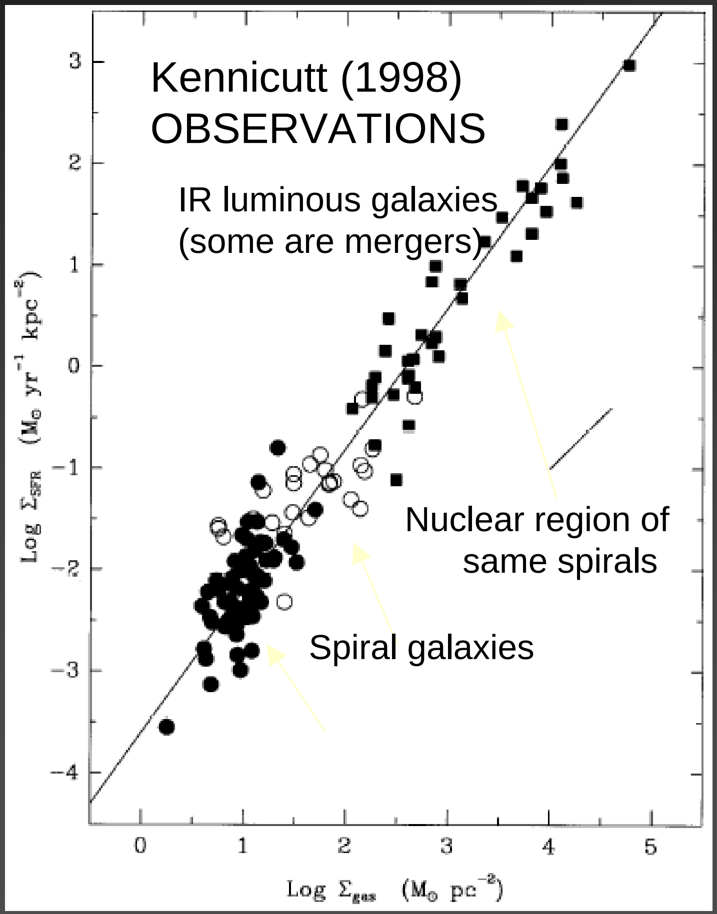
In order to investigate galaxy mergers (and interactions) we build observationally motivated N-body realizations of compound galaxies and simulate their merger using the N-body code GADGET (Springel, Yoshida & White 2000). These simulations include:

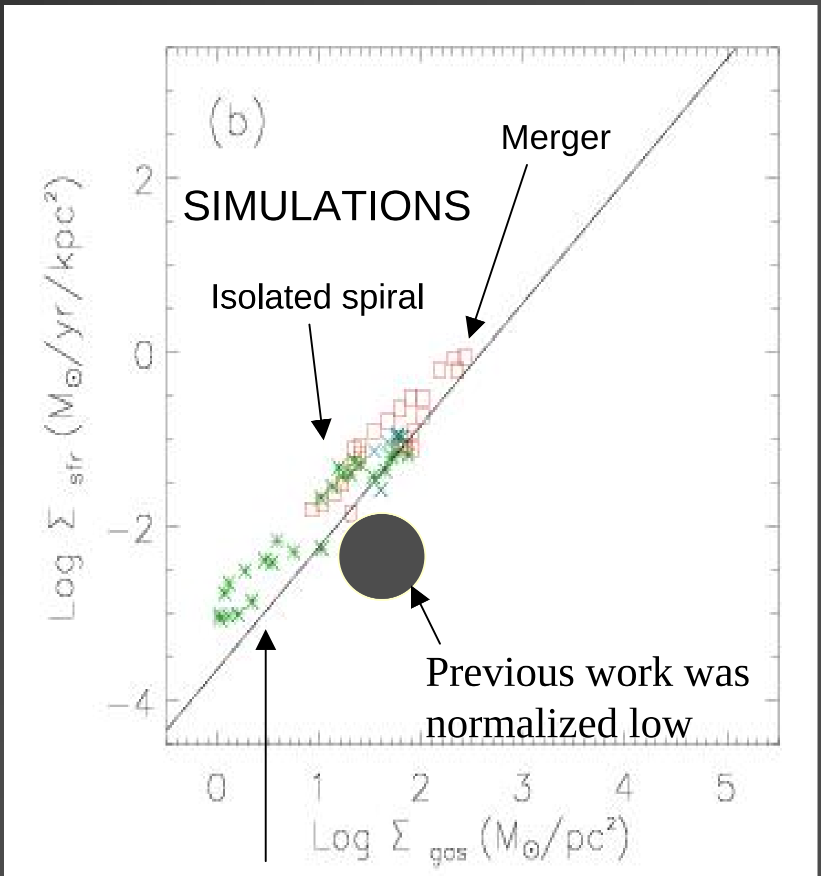
- An improved version of smooth particle hydrodynamics (SPH) with explicitly conserves both energy and entropy. (Springel & Hernquist 2002).
- The radiative cooling of gas (H and He)
- Star formation: $\rho_{sfr} \sim \rho_{gas}/\tau_{dyn}$ for ($\rho_{gas} > \rho_{threshold}$)
- Metal Enrichment
- Stellar Feedback

* Our simulations contain > 100,000 particles per galaxy and the resolution is typically ~100 pc

Designing Star Formation

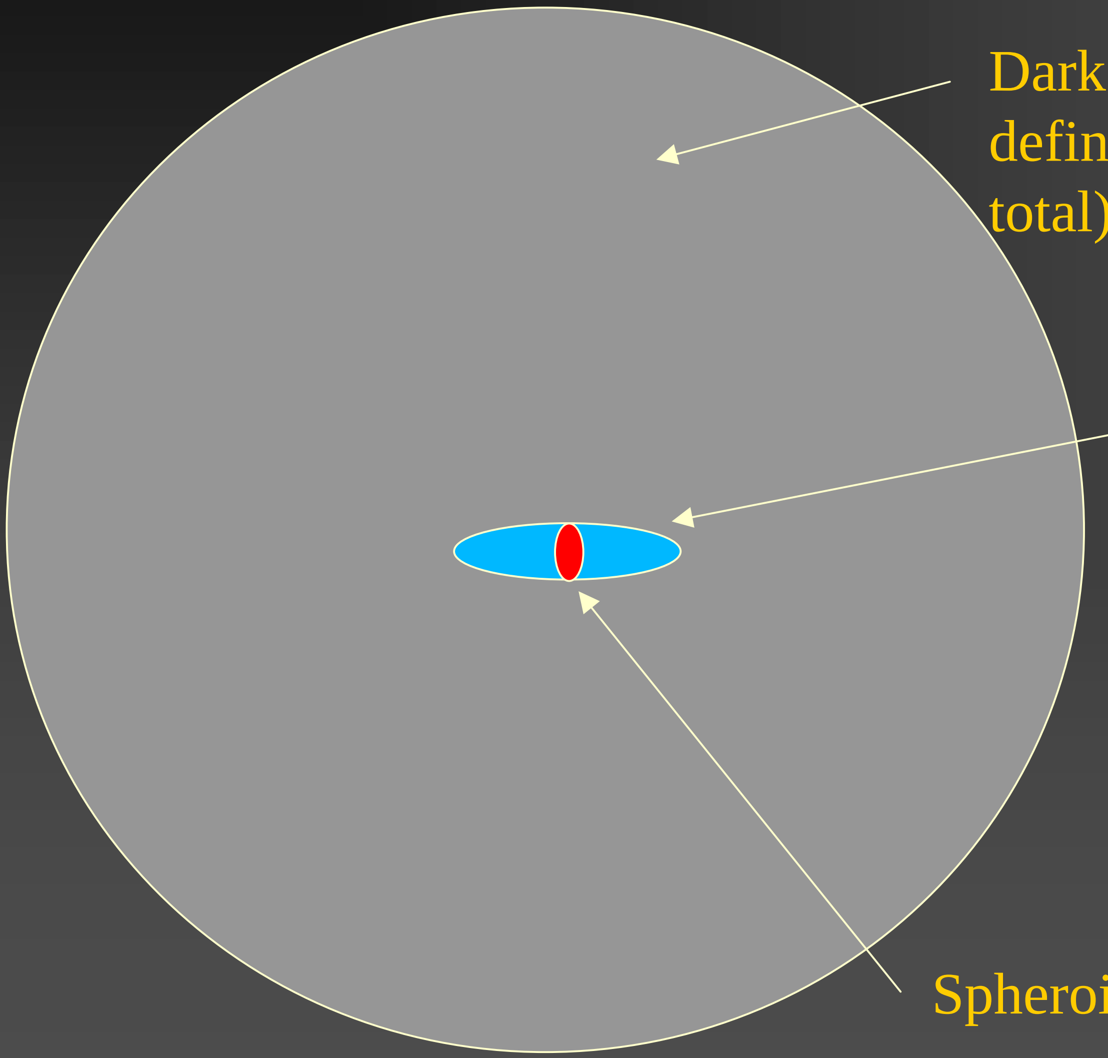
Kennicutt (1998) determined that the surface density of star formation was very tightly correlated with the surface density of gas over a remarkably wide range of gas densities and in a wide variety of galactic states. We use this ‘law’ to calibrate our star formation ($c_\star$) and feedback (β) parameters by requiring an isolated disk to follow the Kennicutt law.





Galaxies tend to fall off the law once gas is depleted.

Initial Conditions

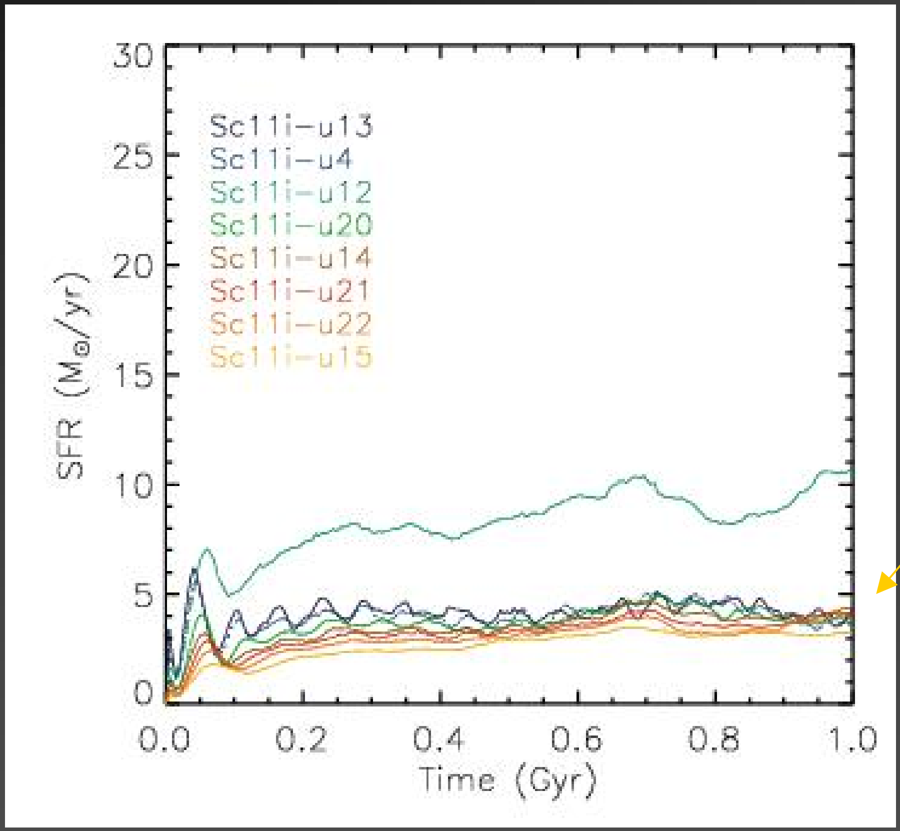


Dark Matter Halo: NFW profile defined by a mass (>90% of the total) and a concentration.

Rotating exponential disk comprised of both stars and gas (the fuel for future star formation).

Spheroidal bulge (in some models)

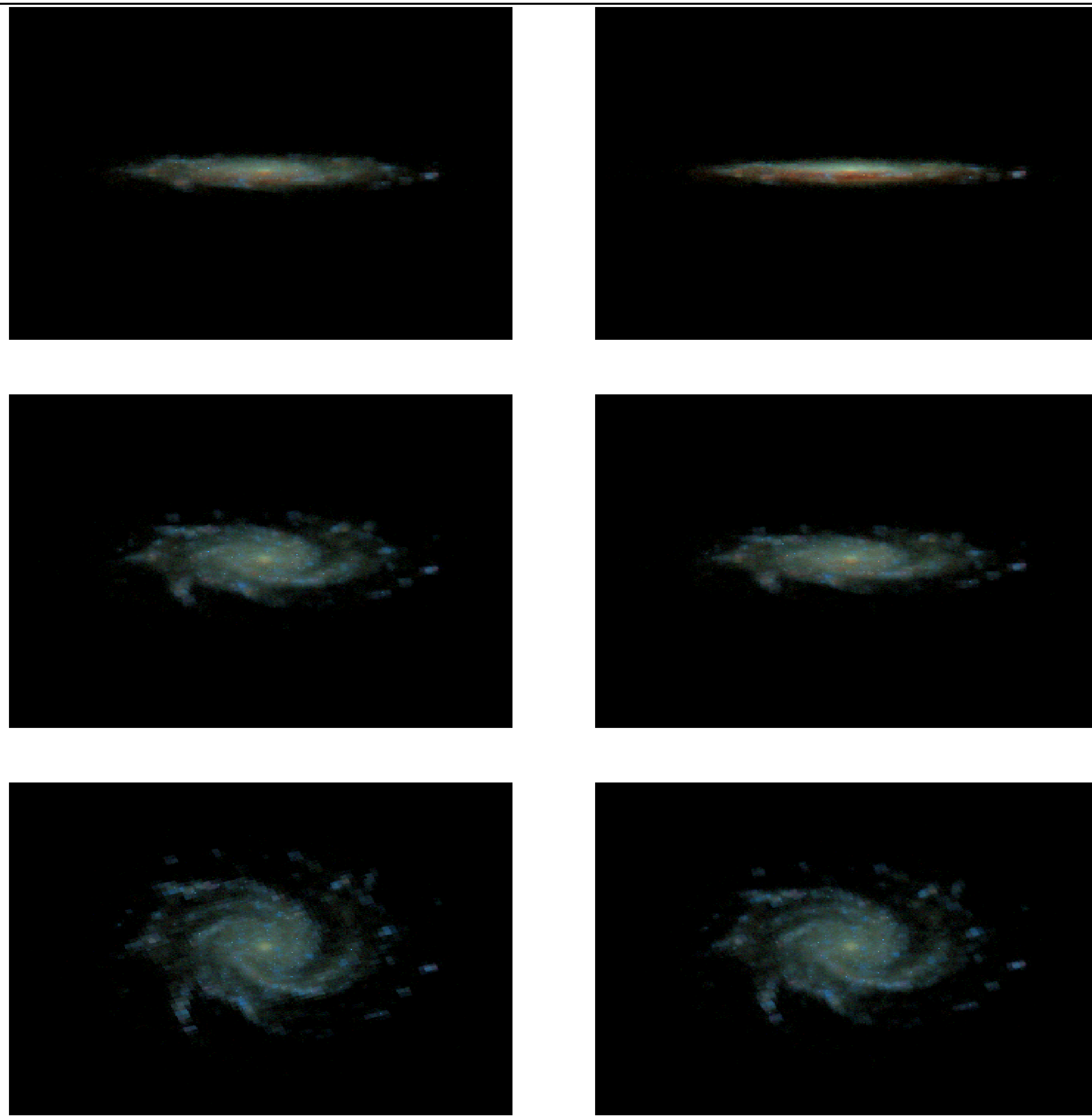
The Star Formation Rate (SFR)



The SFR is roughly constant, as is observed in most “normal” spiral galaxies – GOOD!

→ We can produce and simulate stable disk galaxies.

Images
(with dust) from
Monte Carlo
radiative transfer
code by
Patrik Jonsson



Images
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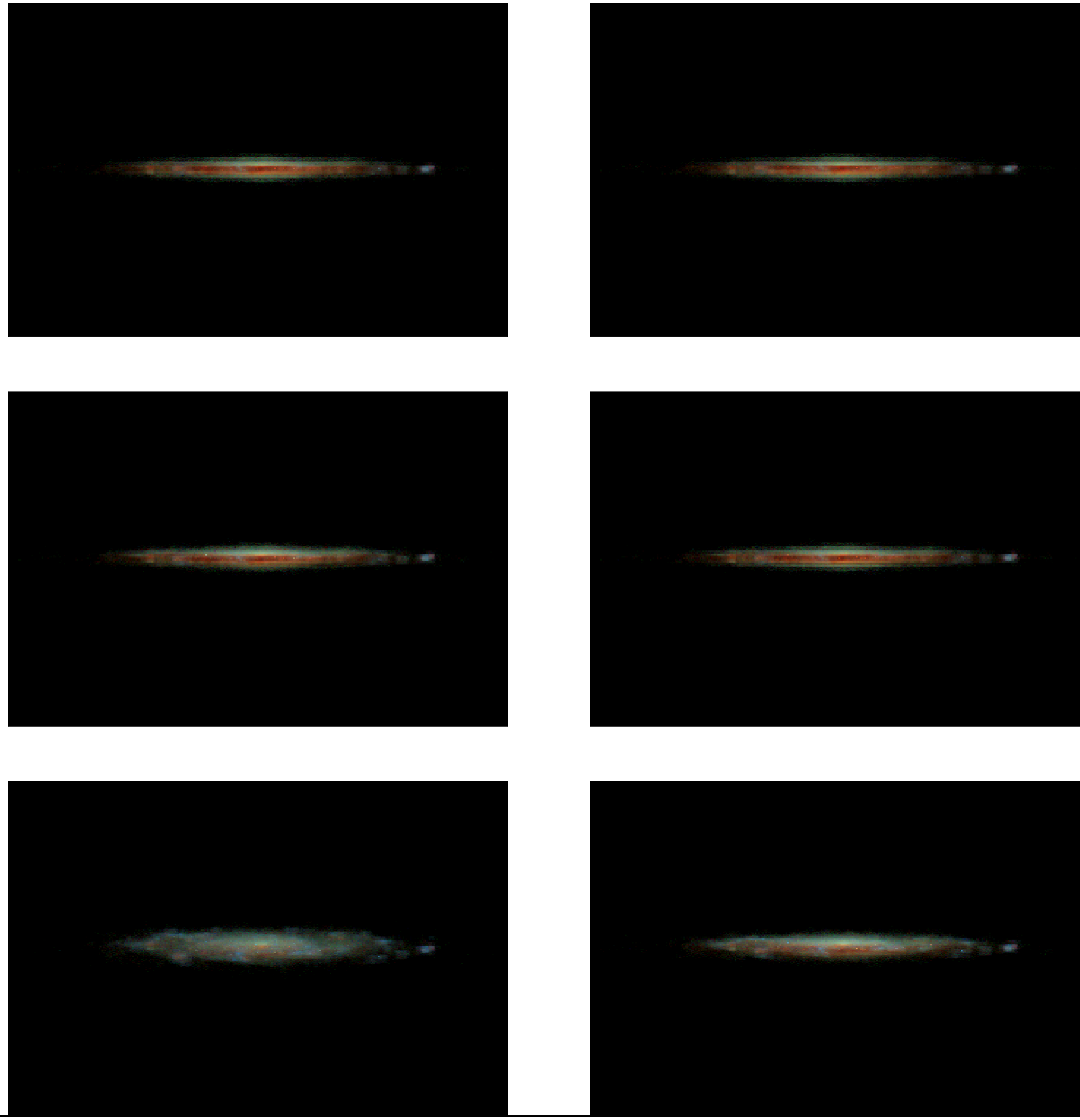
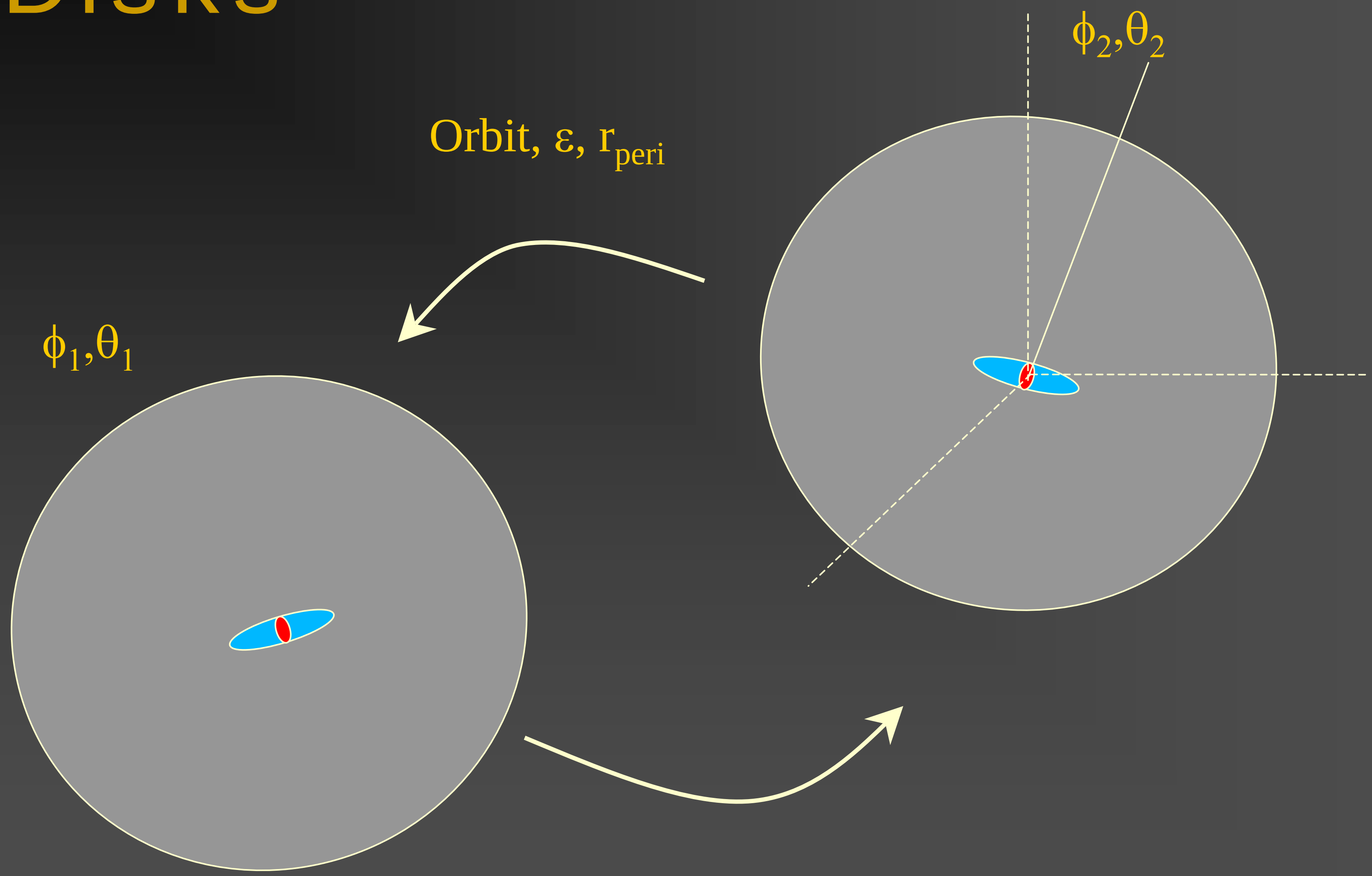
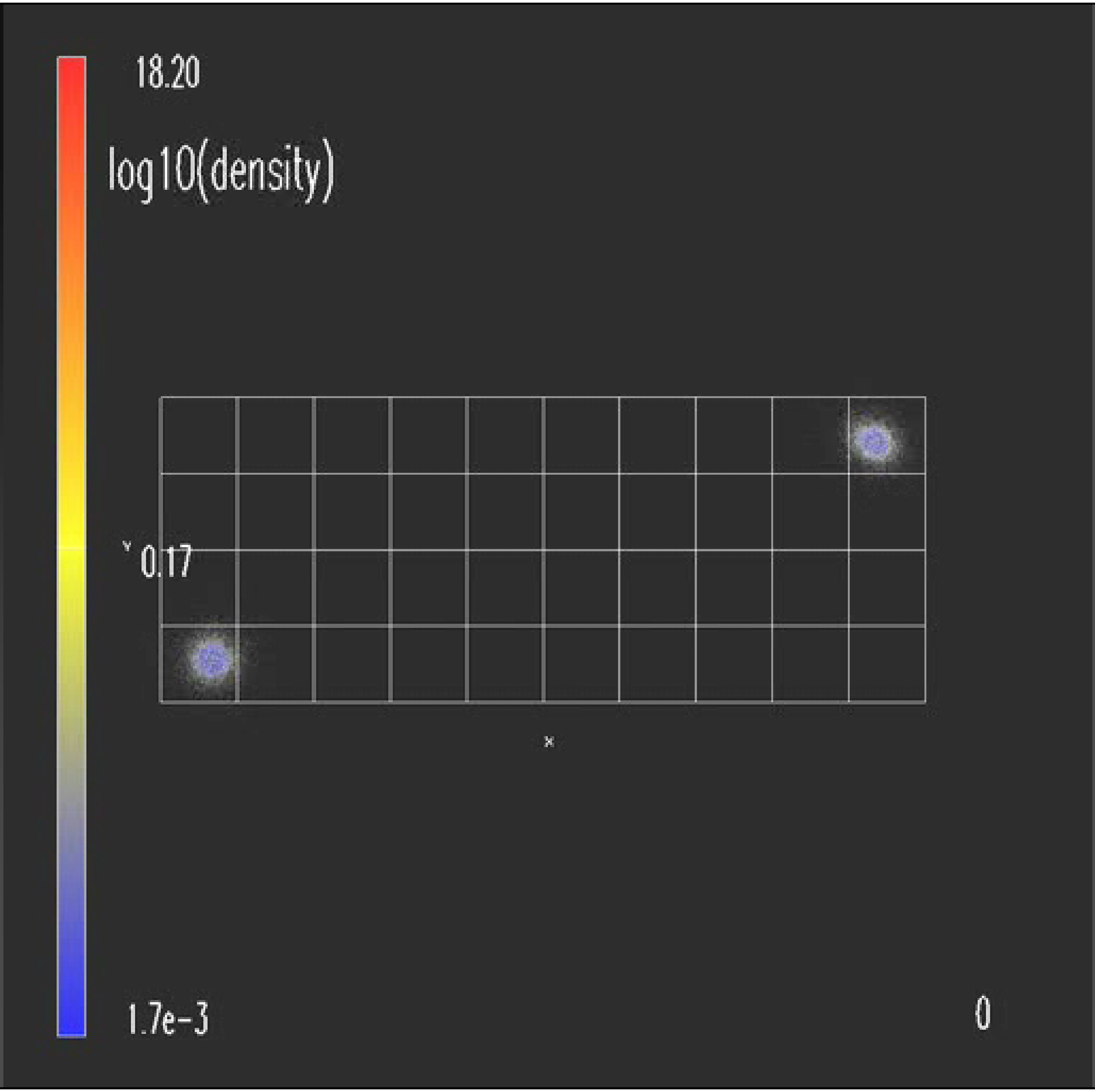


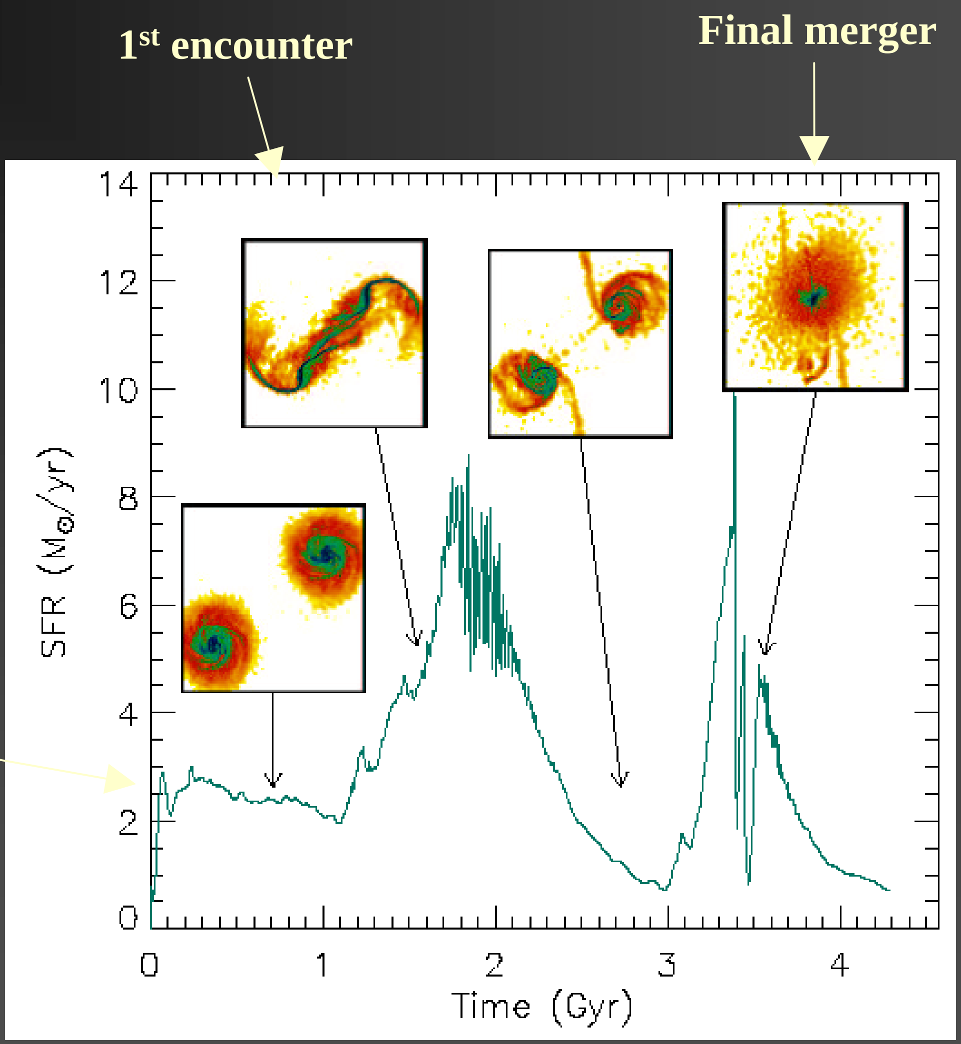
Now Let's Merge Two Disks



Gas Particles color-coded by density



Merger Morphology and Resulting Star Formation

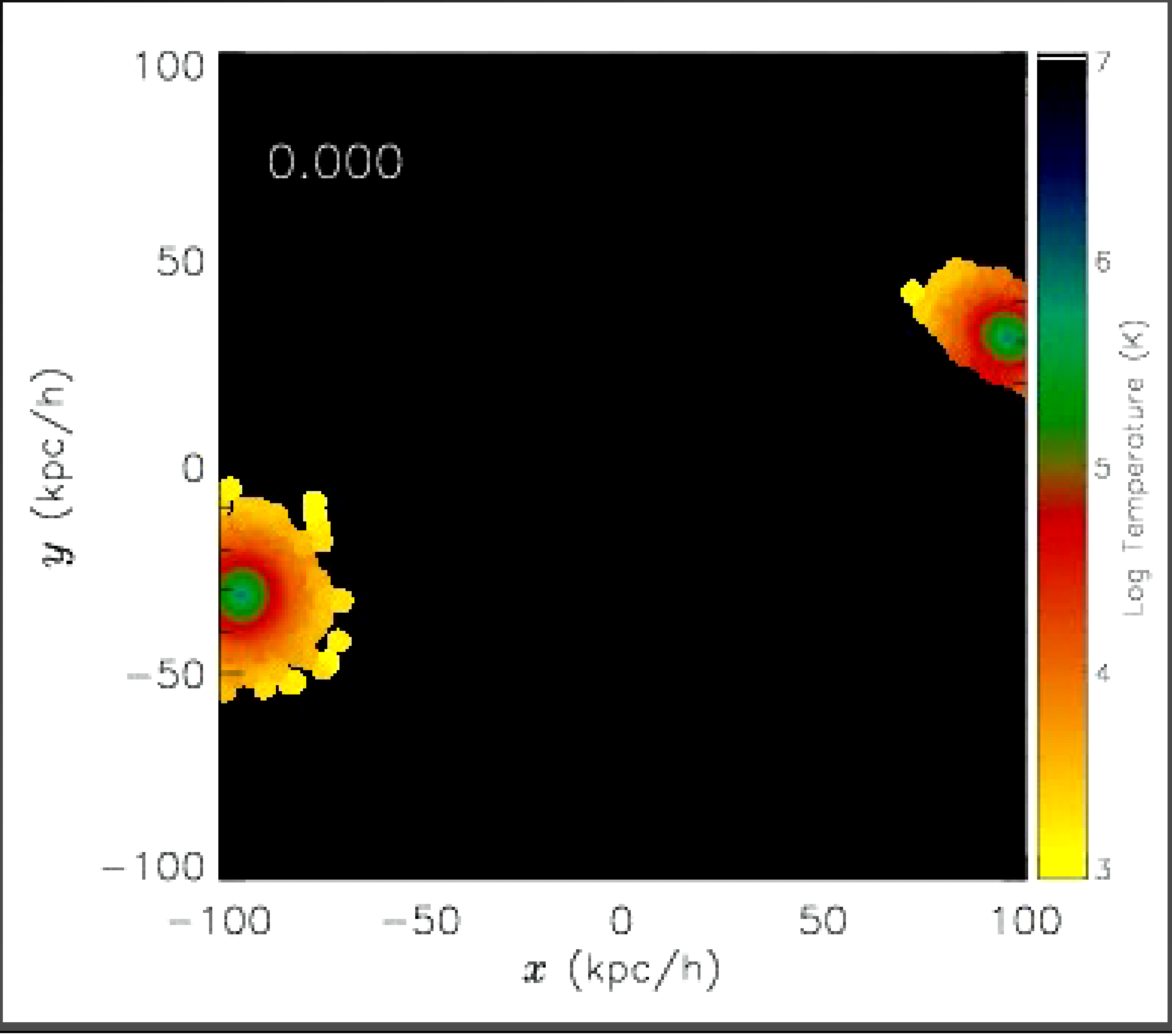


Prograde parabolic orbit, initial separation 250 kpc, pericentric distance 7 kpc

Initially, SFR ~ 2x(disk's quiescent rate)

Gas Temperature during Major Merger

7 kpc slice through orbital plane



10^7 K

10^6 K

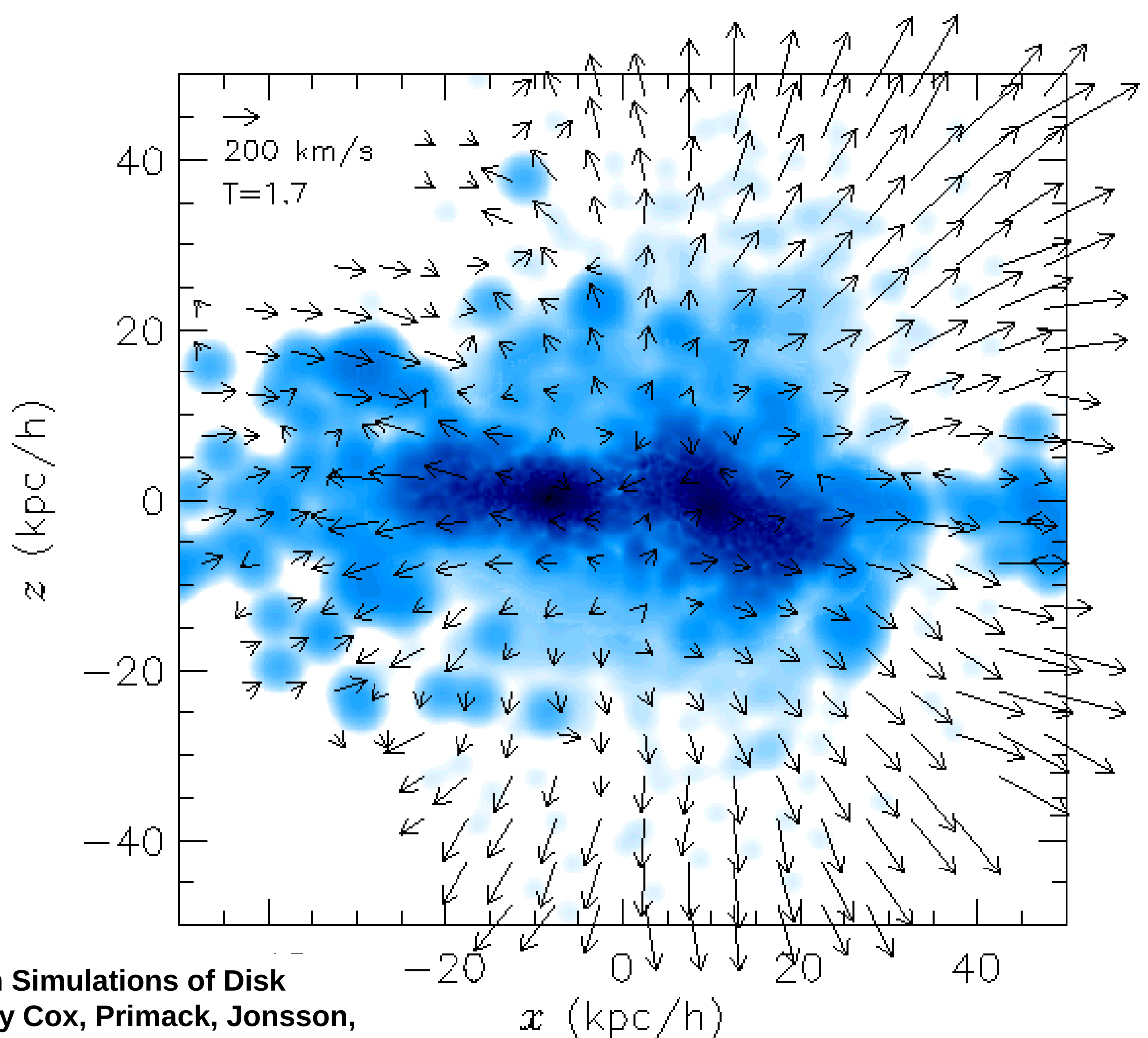
10^5 K

10^4 K

10^3 K

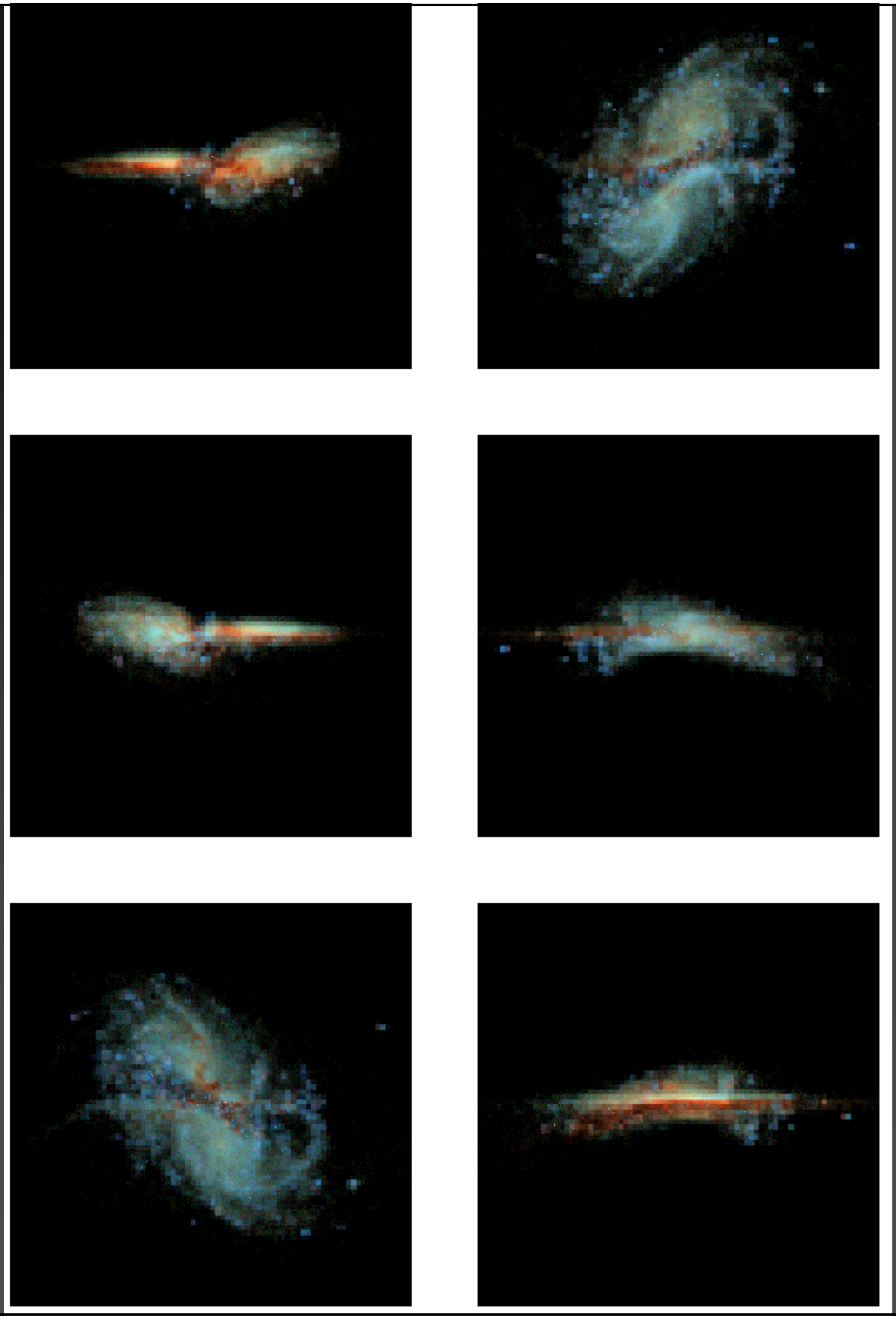
Gas velocity field on color gas density map

7 kpc slice through plane perpendicular to orbital plane

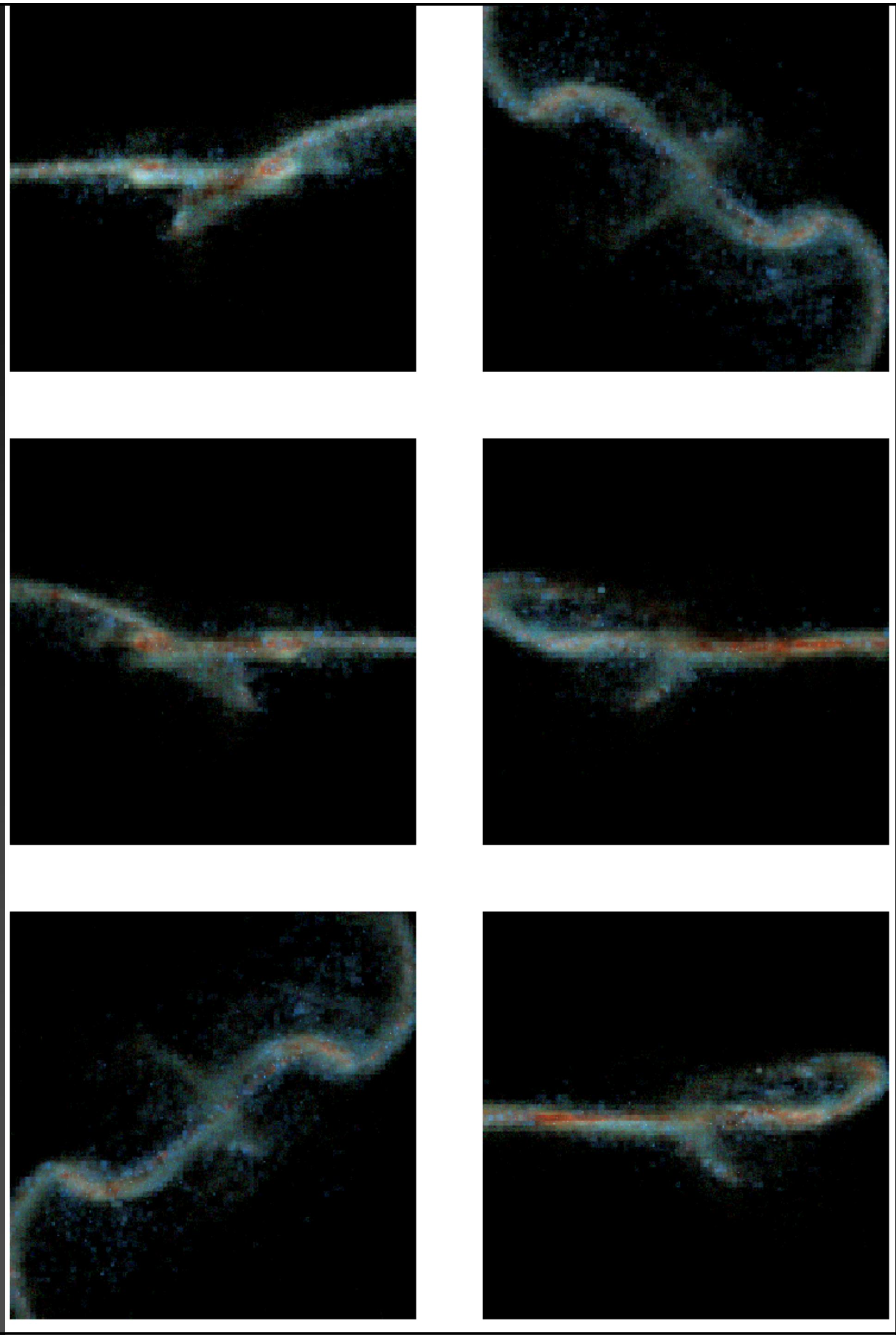


Generating Hot Gas in Simulations of Disk Galaxy Interactions, by Cox, Primack, Jonsson, & Somerville, ApJ, 607, L87 (2004).

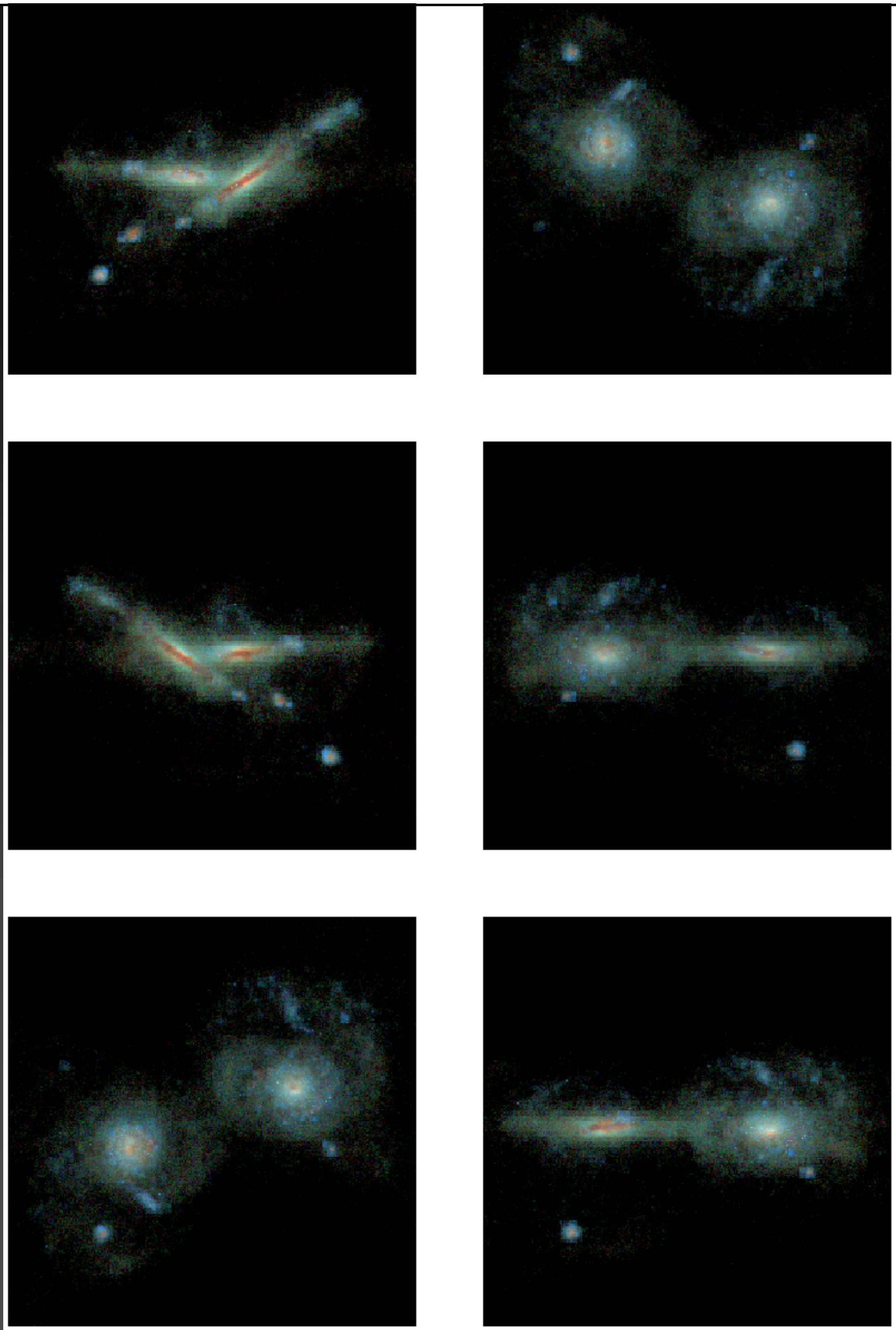
Merger with SEDs and dust: 6 views



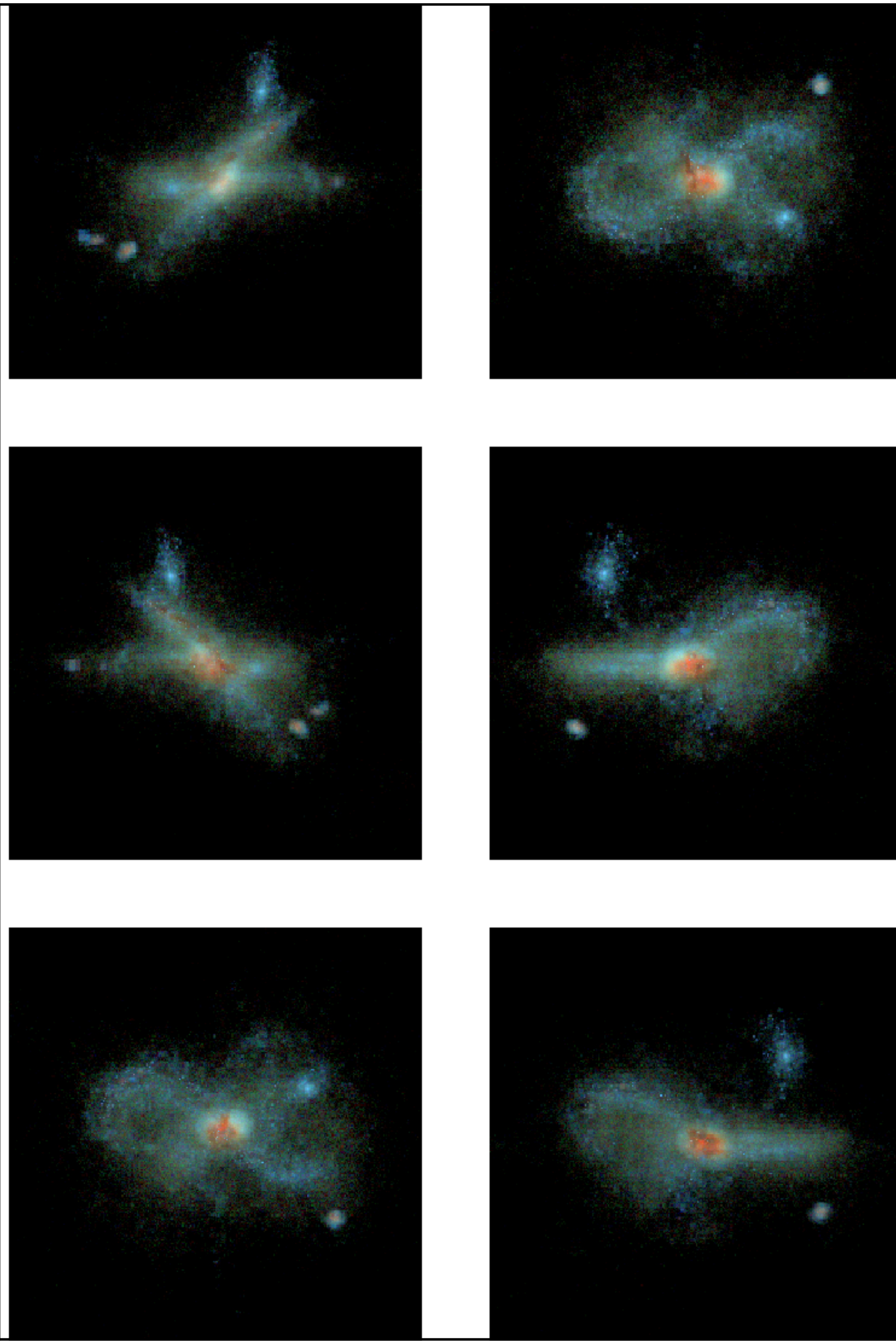
Merger with SEDs and dust: 6 views



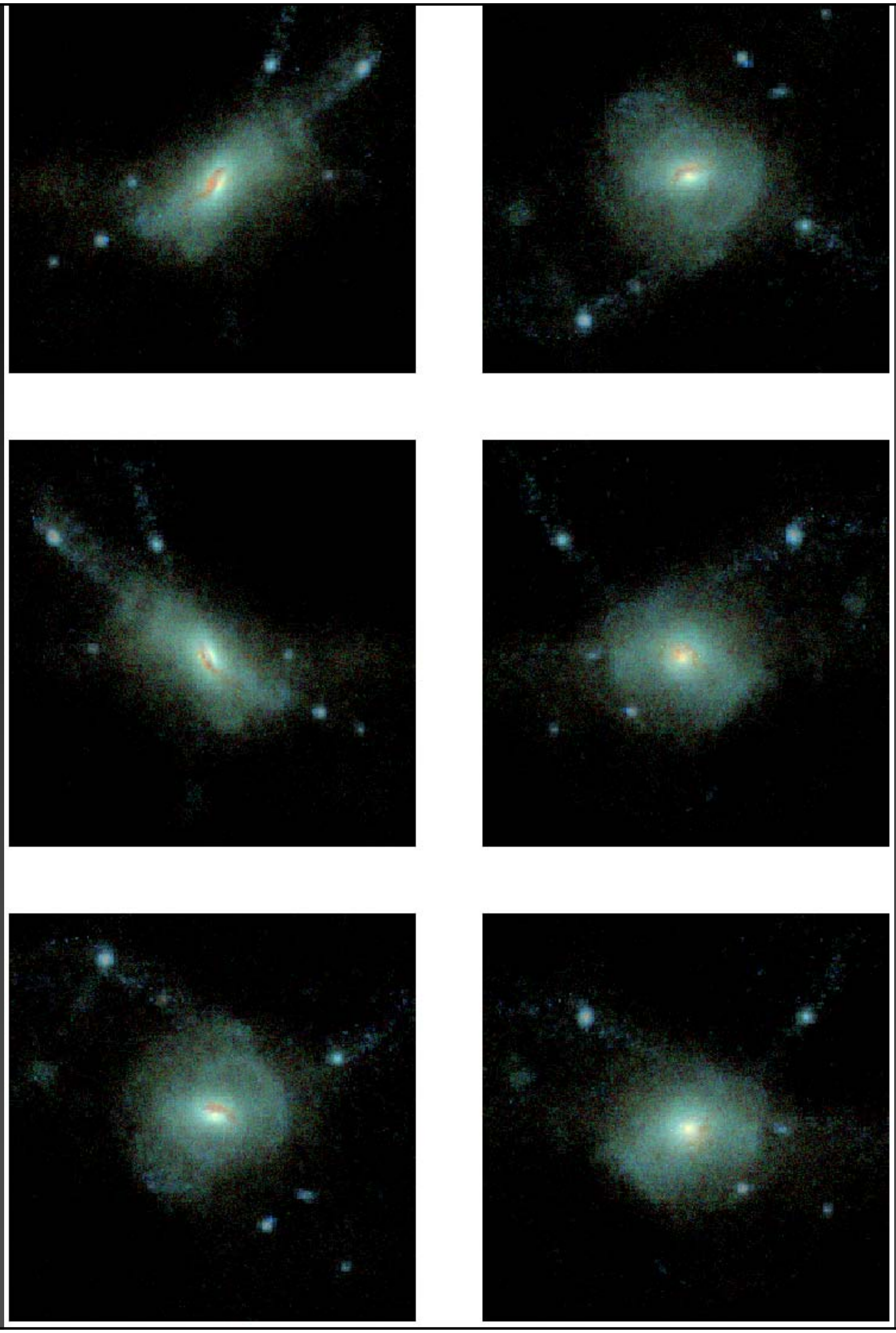
Merger with SEDs and dust: 6 views



Merger with SEDs and dust: 6 views



Merger with SEDs and dust: 6 views



Conclusions

- Mergers induce star formation in a manner generally consistent with both previous simulations of galaxy mergers (Mihos & Hernquist, and Springel) and observations of interacting galaxies.
- The merger between two identical disk galaxies appears to be a viable mechanism to produce elliptical galaxies. But, issues remain: steep stellar cores, detailed kinematics, comparison to K+A galaxies and the fundamental plane of ellipticals.
- MANY more simulations (initial conditions, merger ratios, non-mergers, multiple mergers) are being performed to fully understand the merger process.

Predictions from Galaxy Modeling:

Quantifying Galaxy Morphology and Identifying Mergers

see Lotz, Primack & Madau, AJ in press (astro-ph/0311352)

Measuring Galaxy Morphology

- by "eye" - Hubble tuning fork E-Sa-Sb-Sc-Sd-(Irr)

- parametric

  1-D profile fit ($r^{1/4}$, exponential, Sersic)

  2-D profile fit (bulge+disk; GIM2D, GALFIT)

  → doesn't work for irregular/merging galaxies

- non-parametric

  "CAS" - concentration, asymmetry, clumpiness

  neural-net training

  shaplet decomposition

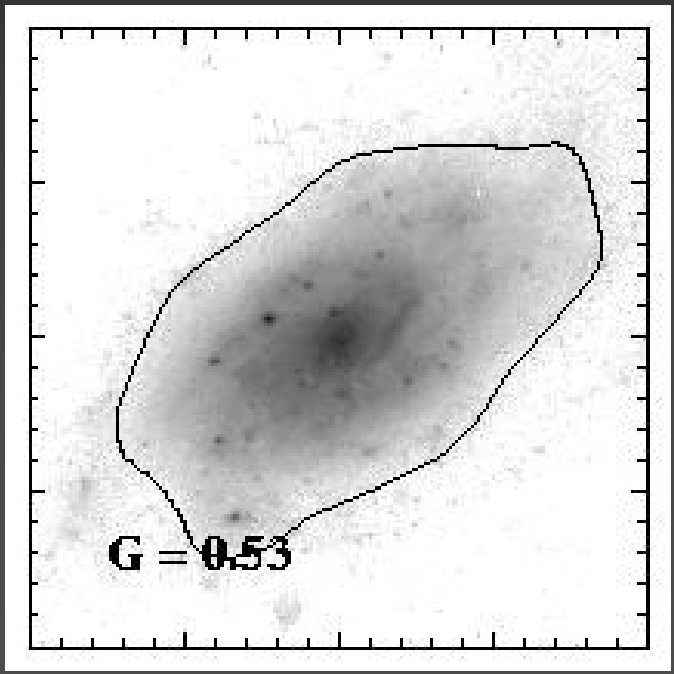
  new: Gini Coefficient (Abraham et al. 2003)

  2nd order moment of brightest regions

the Gini Coefficient

used in economics to measure distribution of wealth in population
→ distribution of flux in galaxy's pixels (Abraham et al. 2003)

G=0 for completely egalitarian society (uniform surf brightness)
G=1 for absolute monarchy (all flux in single pixel)
(G = 0.445 for US in 1999)



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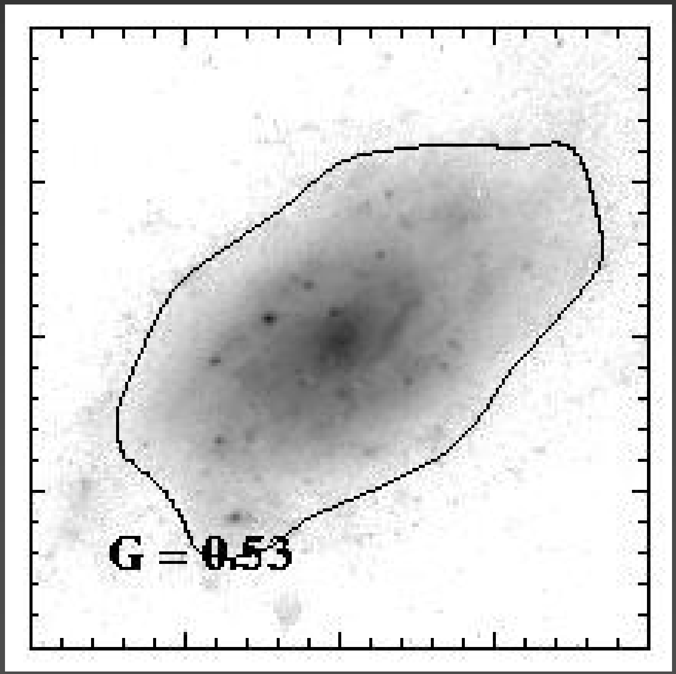

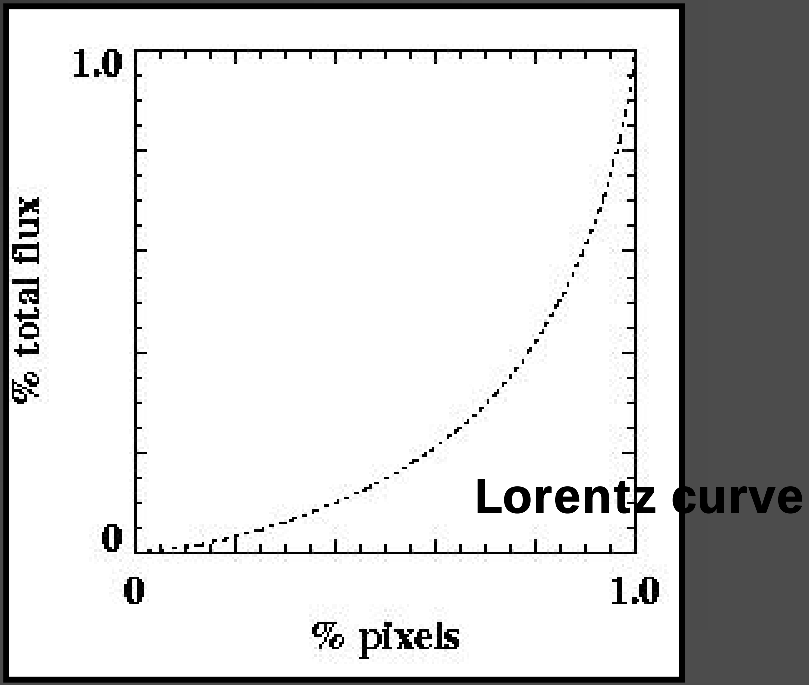

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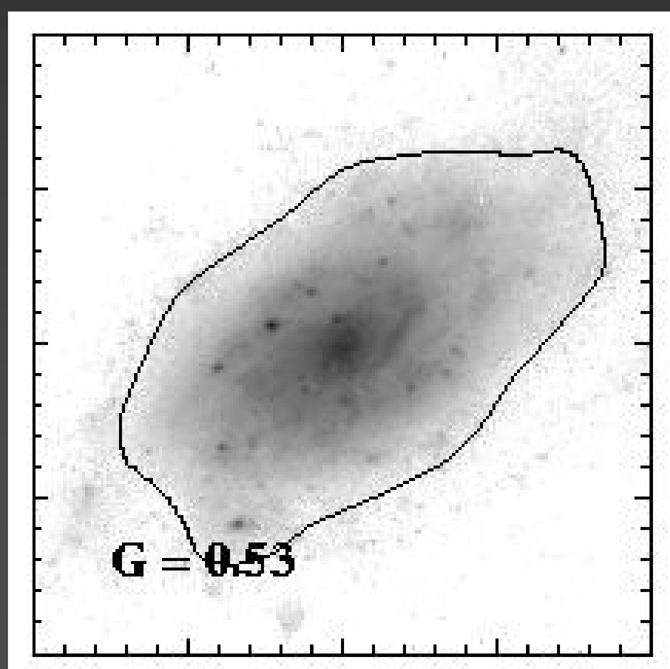

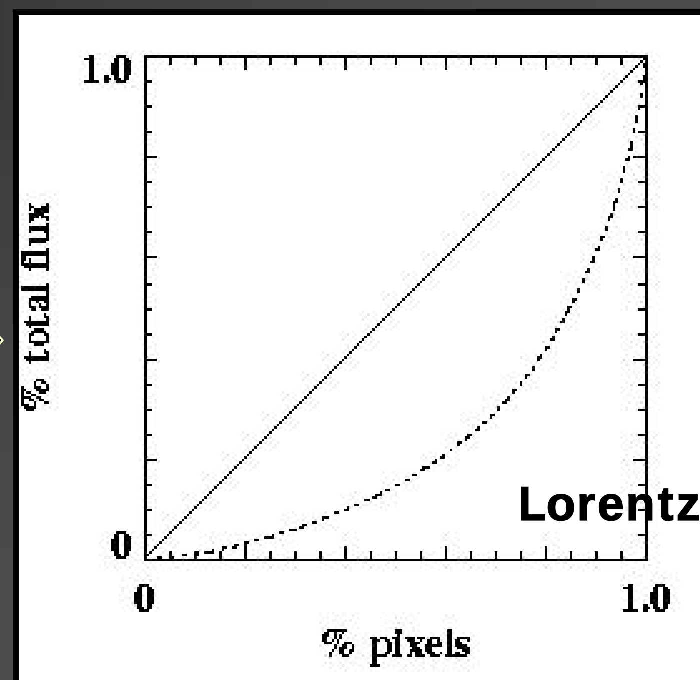

Lorentz curve

the Gini Coefficient

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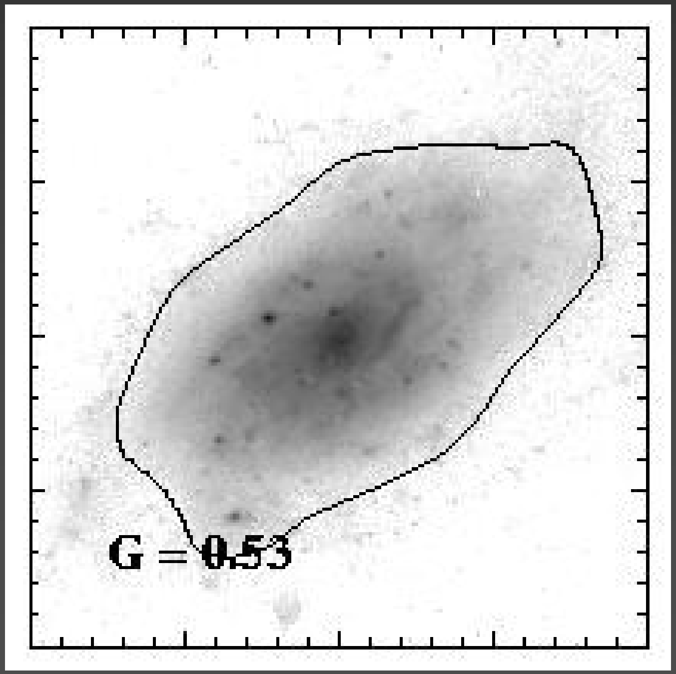

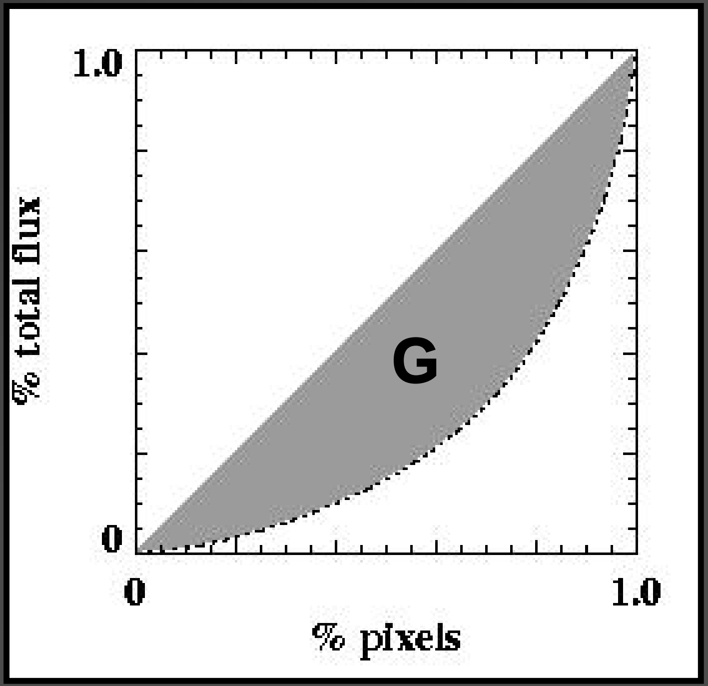

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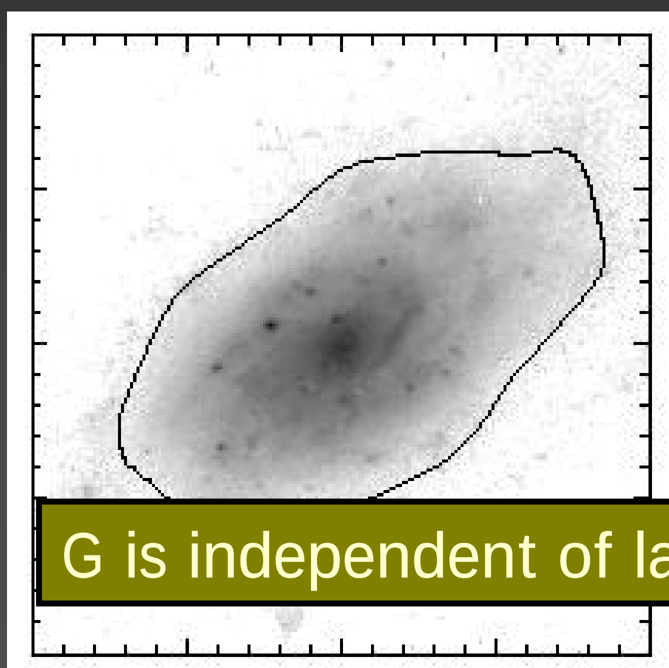
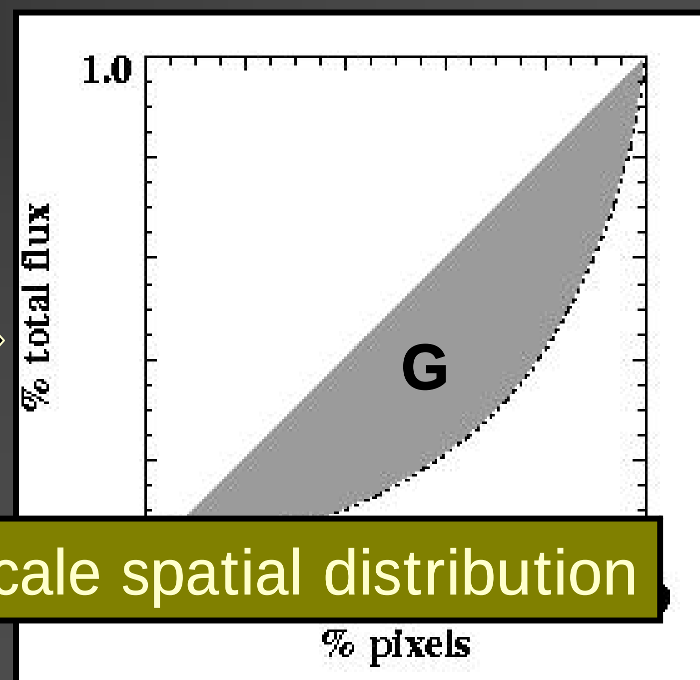




G is independent of large-scale spatial distribution

2^{nd} order moment of light

$M_{total} = \sum_i f_i \cdot r_i^2$ (minimize to find center)

this depends on size + luminosity

→ find *relative* moment of brightest regions

$$M_{20} = \log_{10} \frac{\sum_i^n f_i \cdot r_i^2}{M_{total}} \quad \text{where} \quad \sum_i^n f_i = 0.2 \sum_i f_i$$

- very similar to C (= log ($r_{80\%}/r_{20\%}$))
  but does NOT assume particular geometry

- more sensitive to merger signatures (double nuclei)

defining the galaxy map

G + M_{20} depend on which pixels/spatial regions are assigned to galaxy

want this "map" to be insensitive to S/N, surface brightness, and distance/redshift

➔ pixels with $\mu > \mu(r_p)$ are assigned to galaxy

Petrosian radius r_p based on curve of growth

$$\eta = \frac{\mu(r_p)}{\langle \mu(r < r_p) \rangle} \equiv 0.2$$

insensitive to S/N + surface brightness dimming

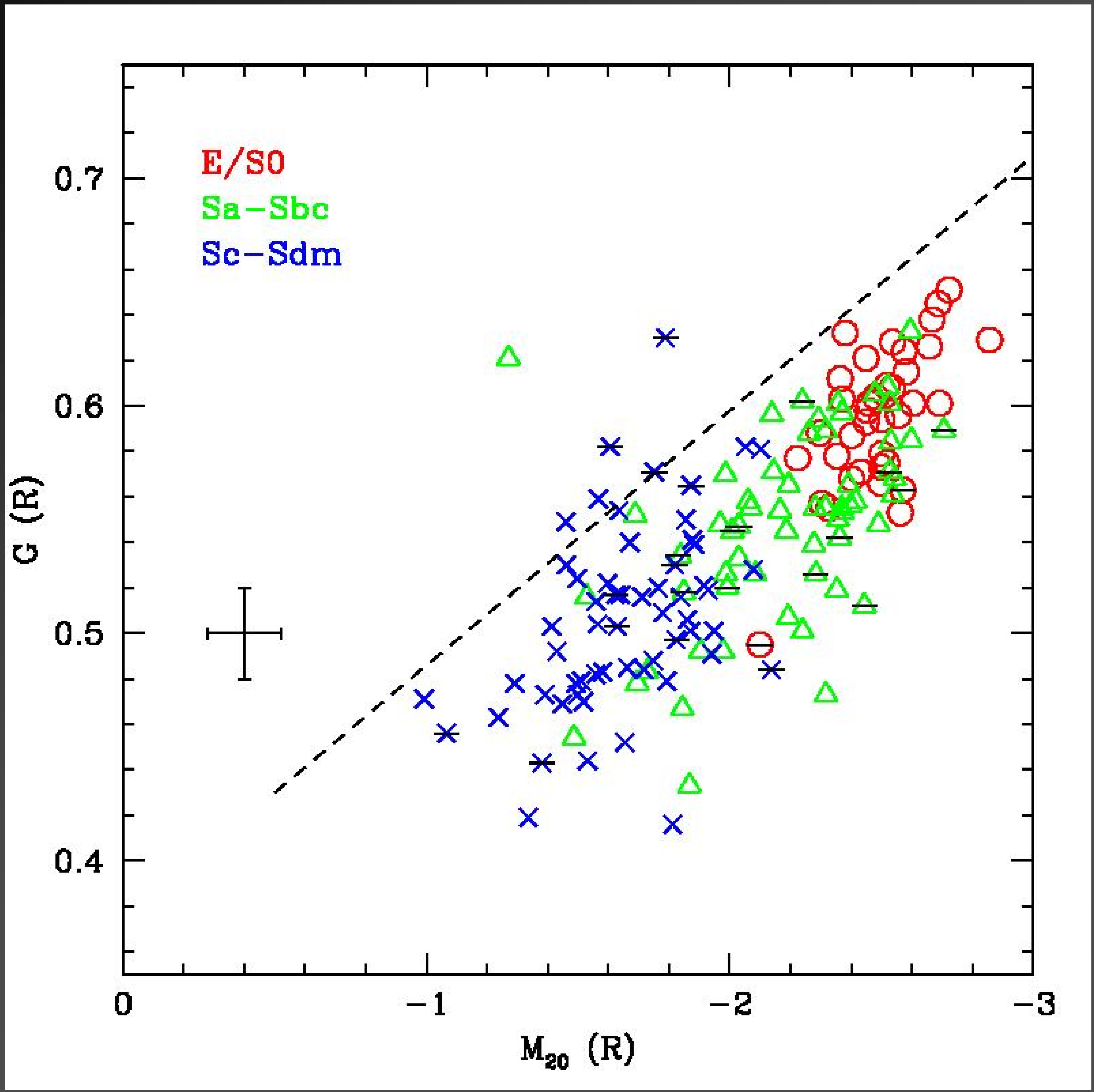
Local Galaxy G-M20 relation

Frei et al 1996: ~100 bright local Hubble types
B/g (~4500 AA) + R/r (~6500 AA)

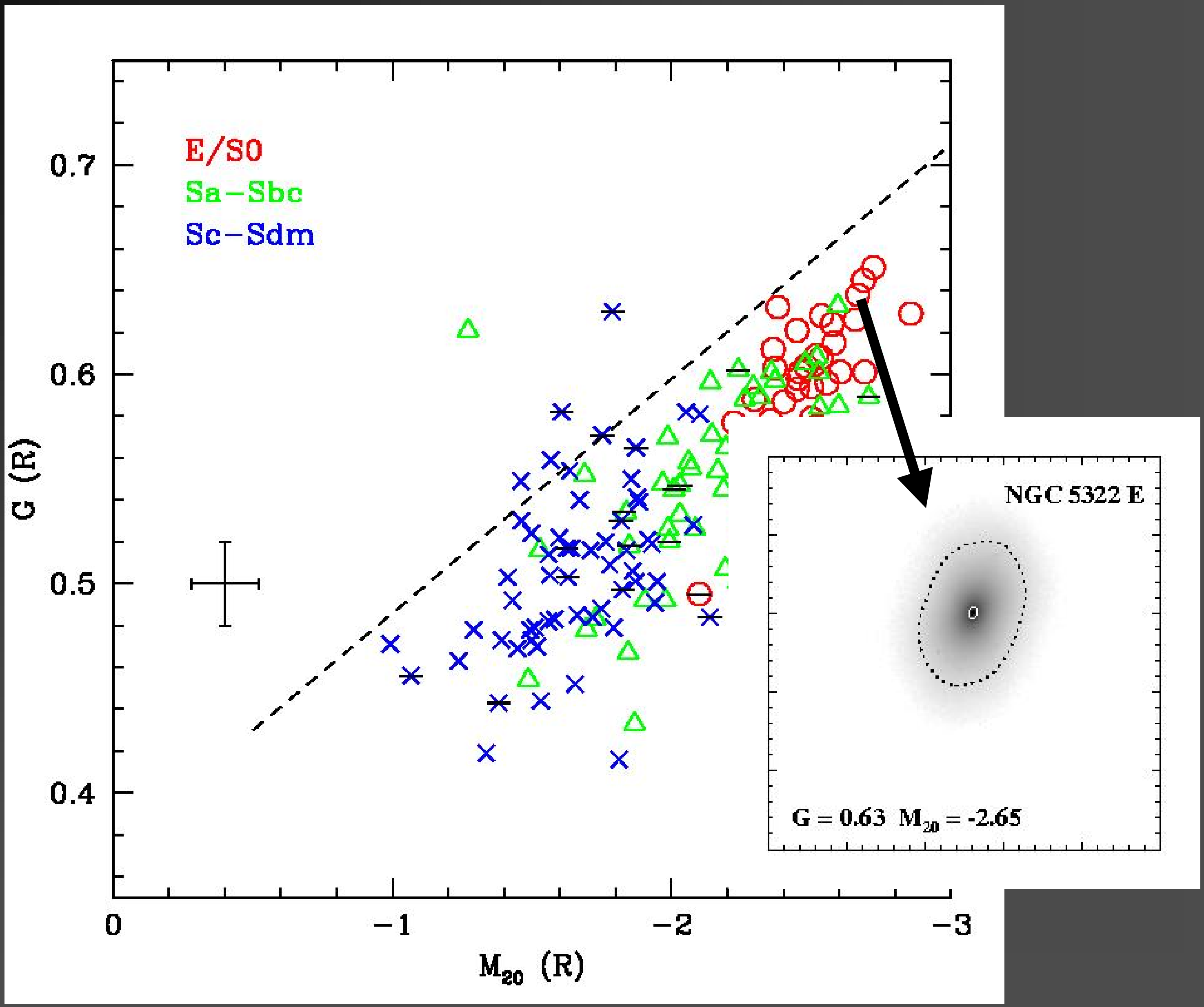
SDSS DR1: ~50 local bright (u<14) galaxies
u (~3600 AA), g (~4700 AA), r(~6200 AA)

Borne et al 2000: ~100 HST WFPC2 $z < 0.2$ ULIRGs
F814W (~ 6500 AA rest-frame)

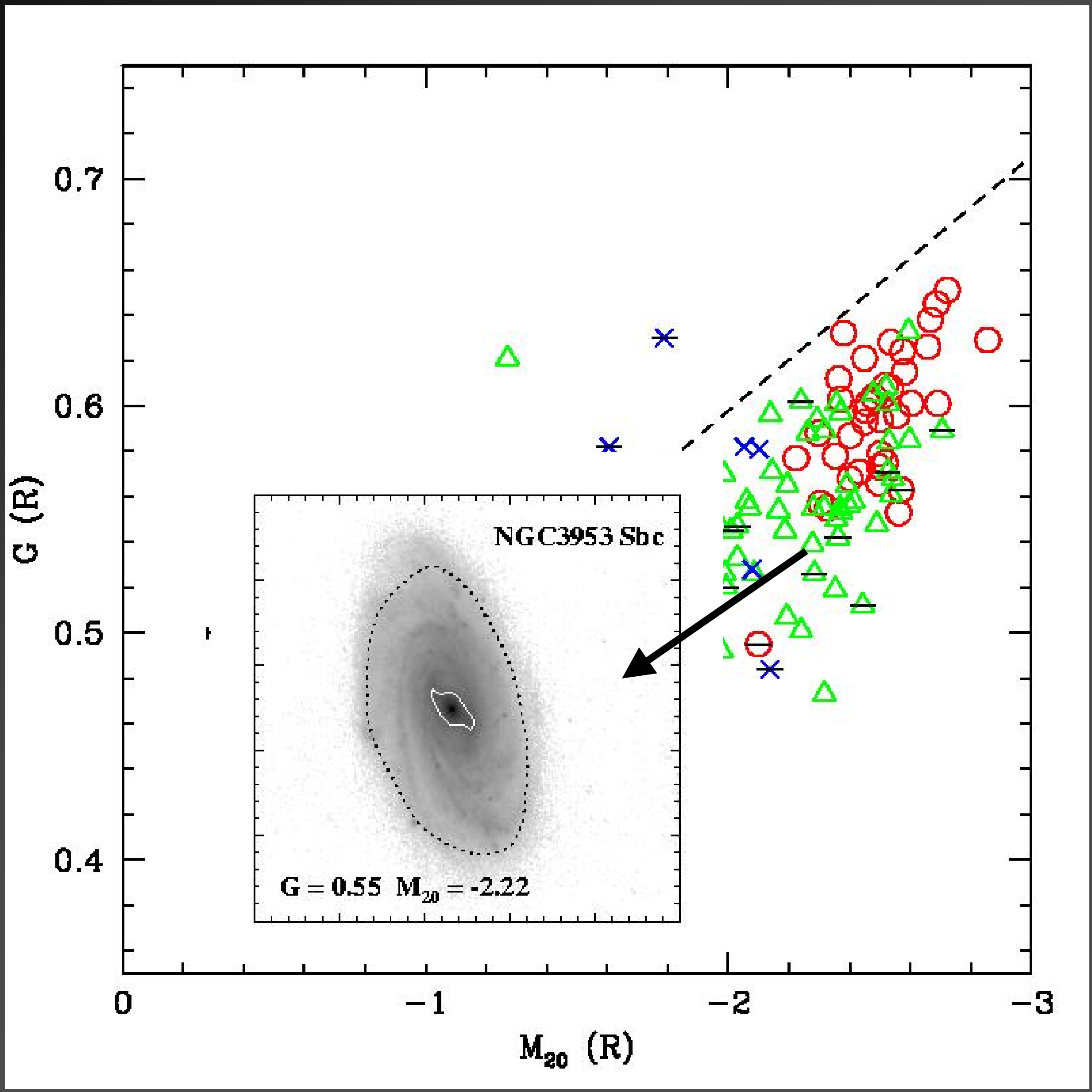
Local Galaxy G-M20 relation



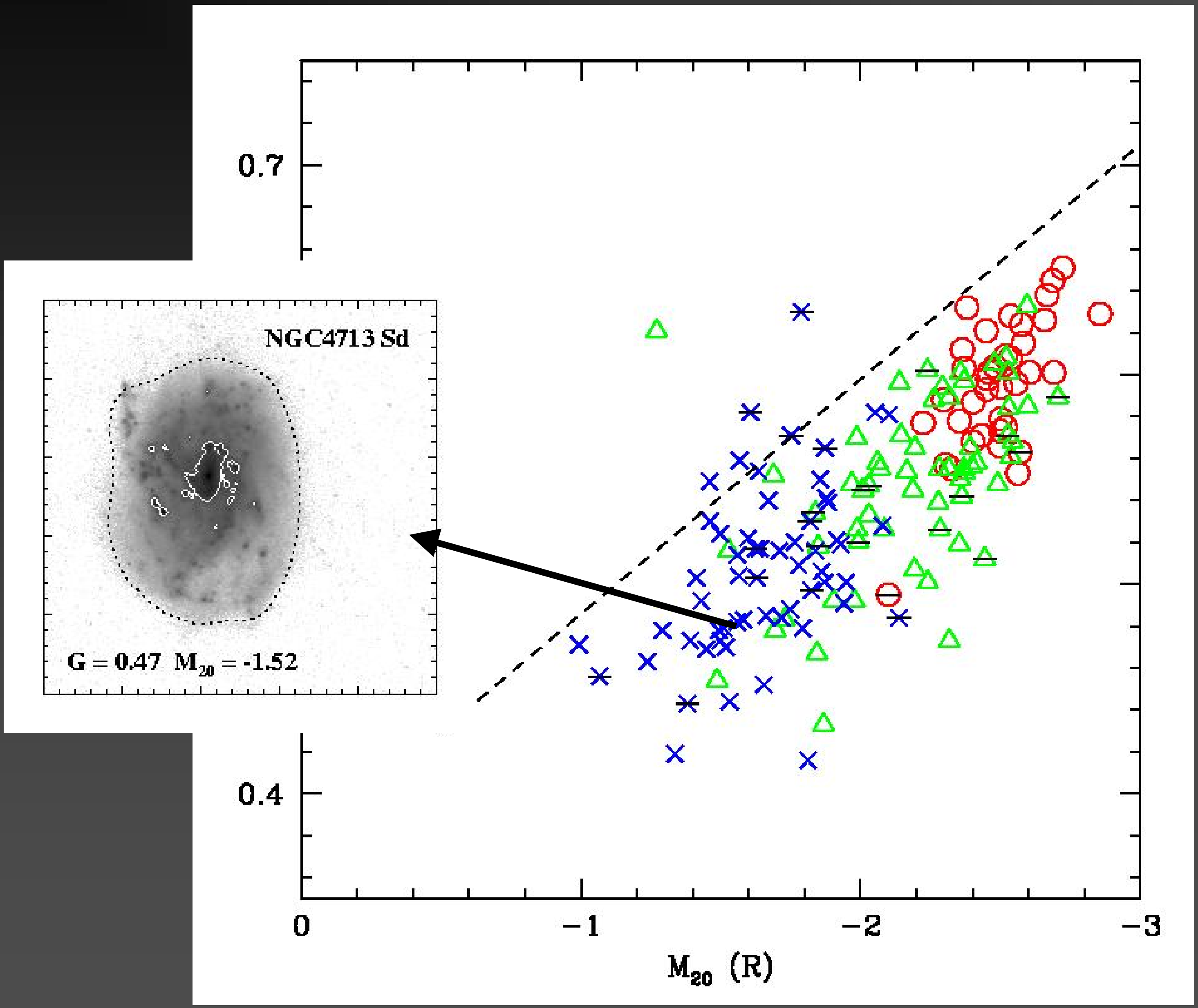
Local Galaxy G-M20 relation



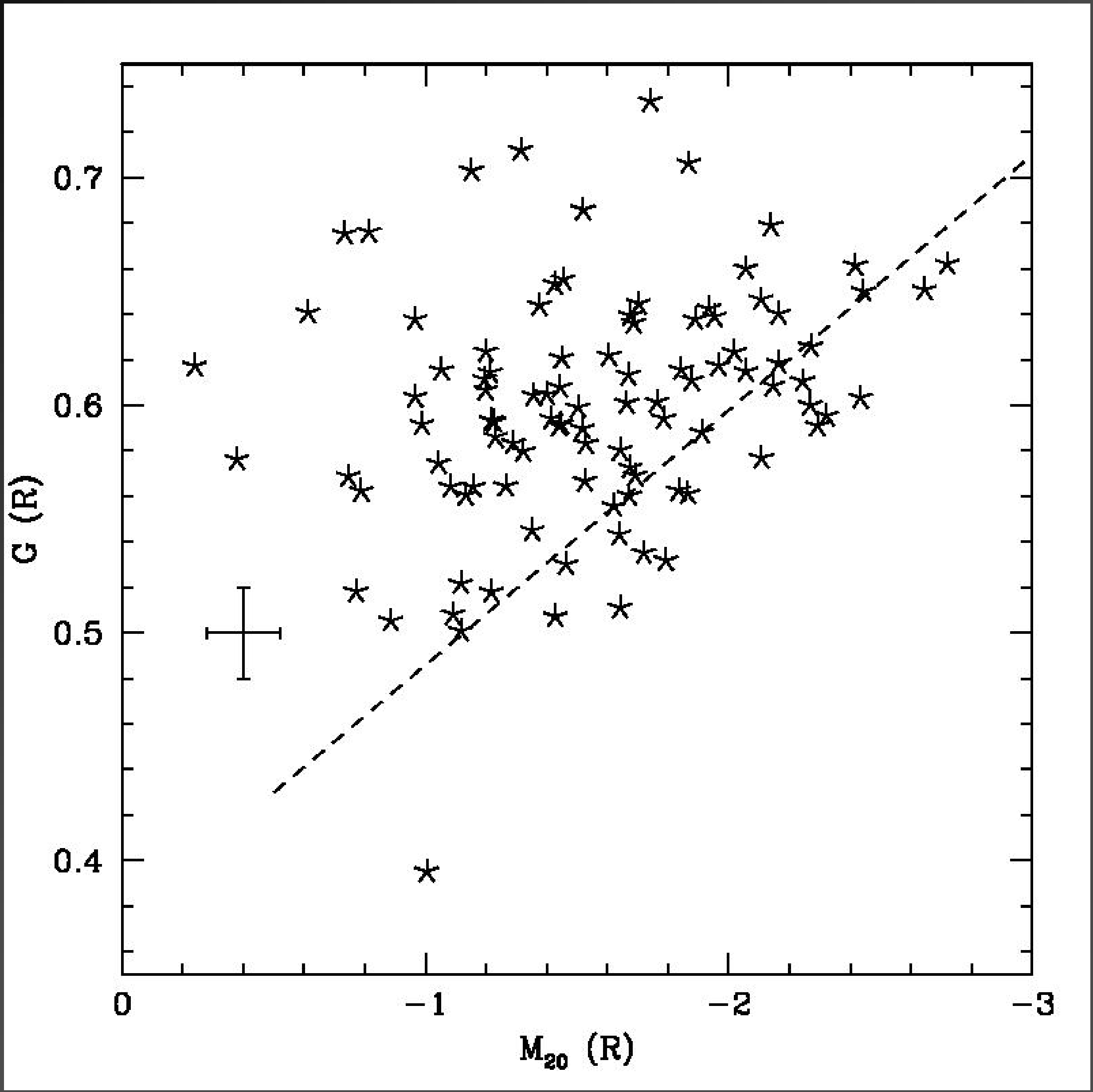
Local Galaxy G-M20 relation



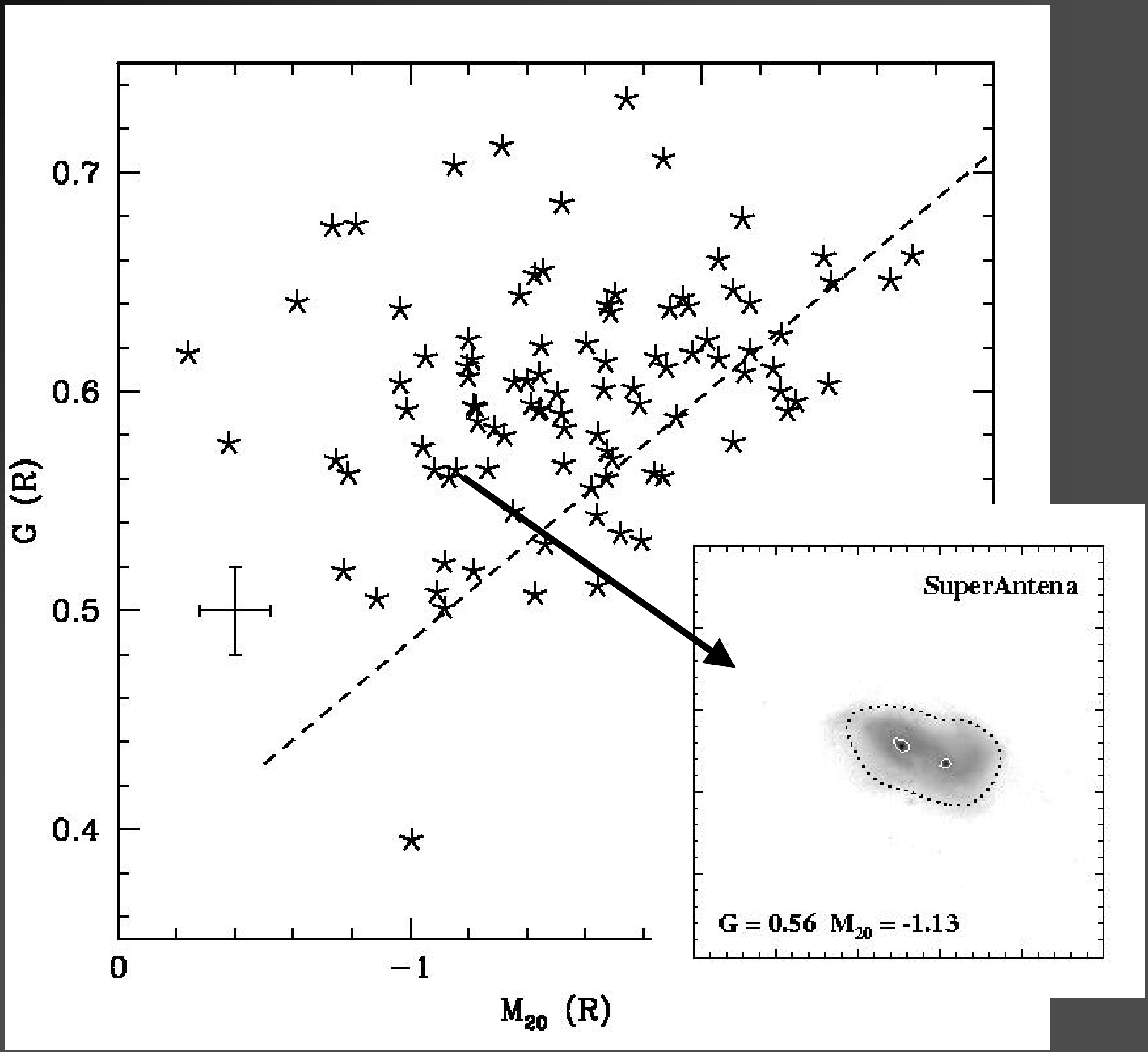
Local Galaxy G-M20 relation



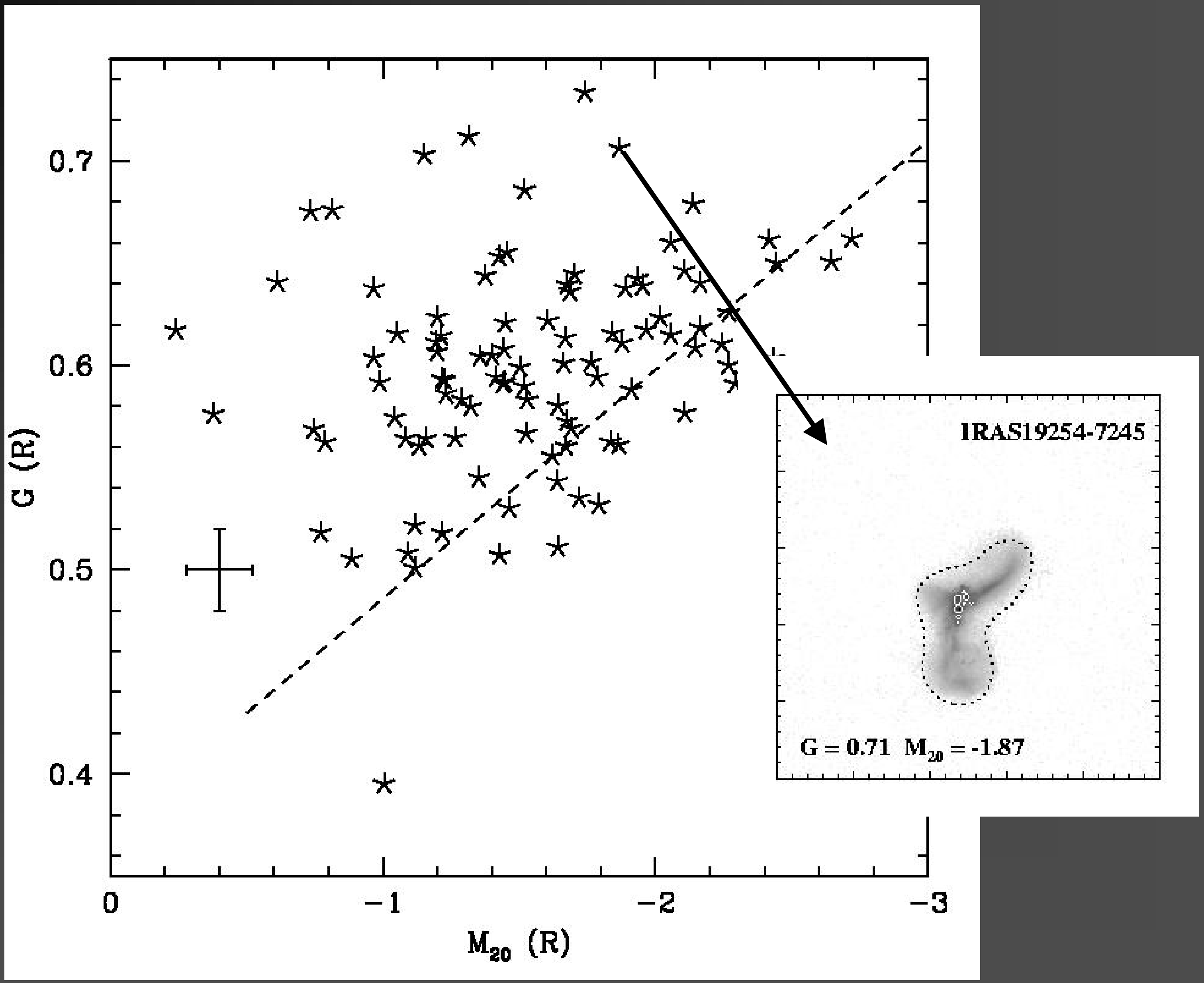
Local Galaxy G-M20 relation



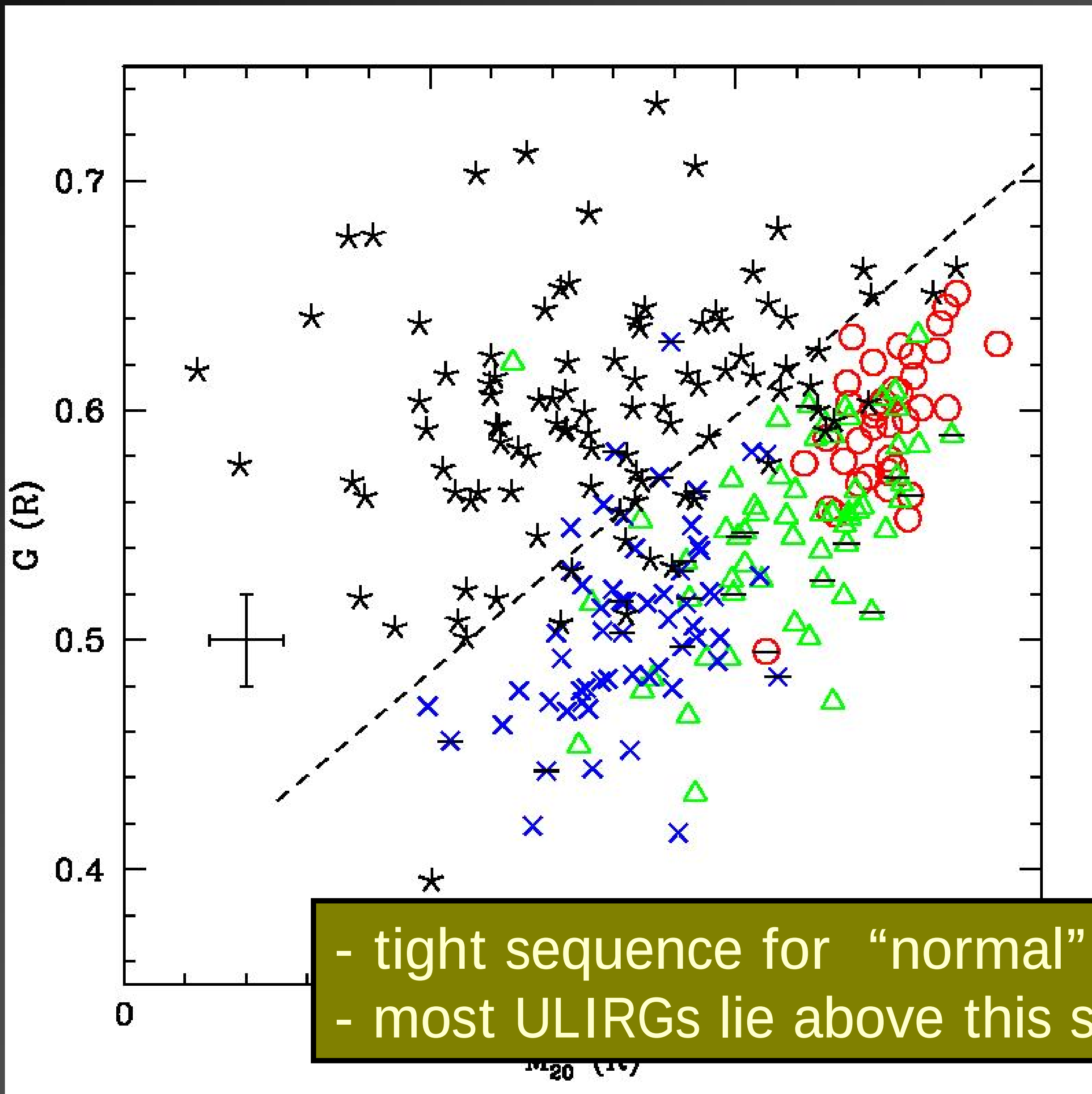
Local Galaxy G-M20 relation



Local Galaxy G-M20 relation

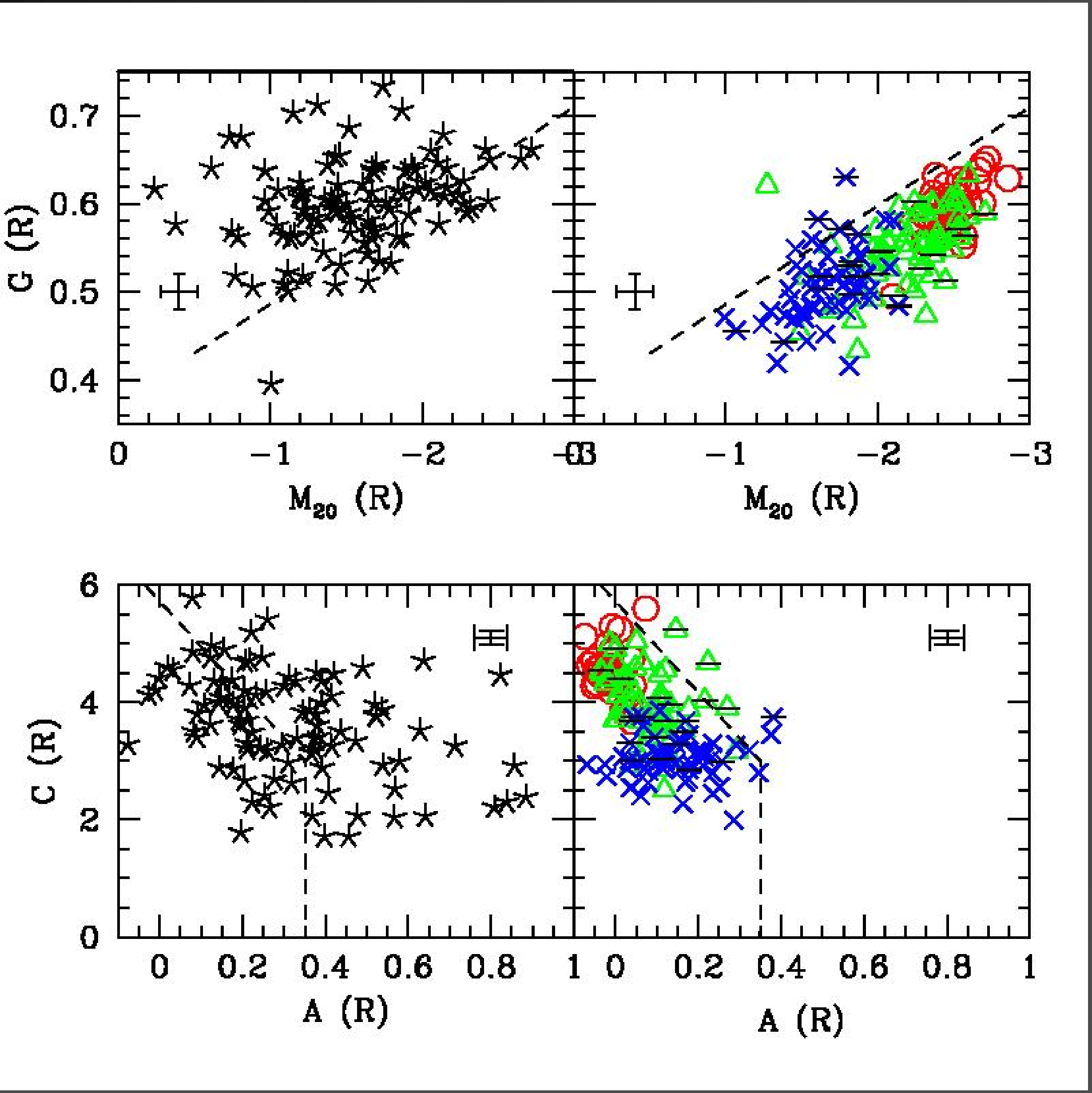


Local Galaxy G-M20 relation



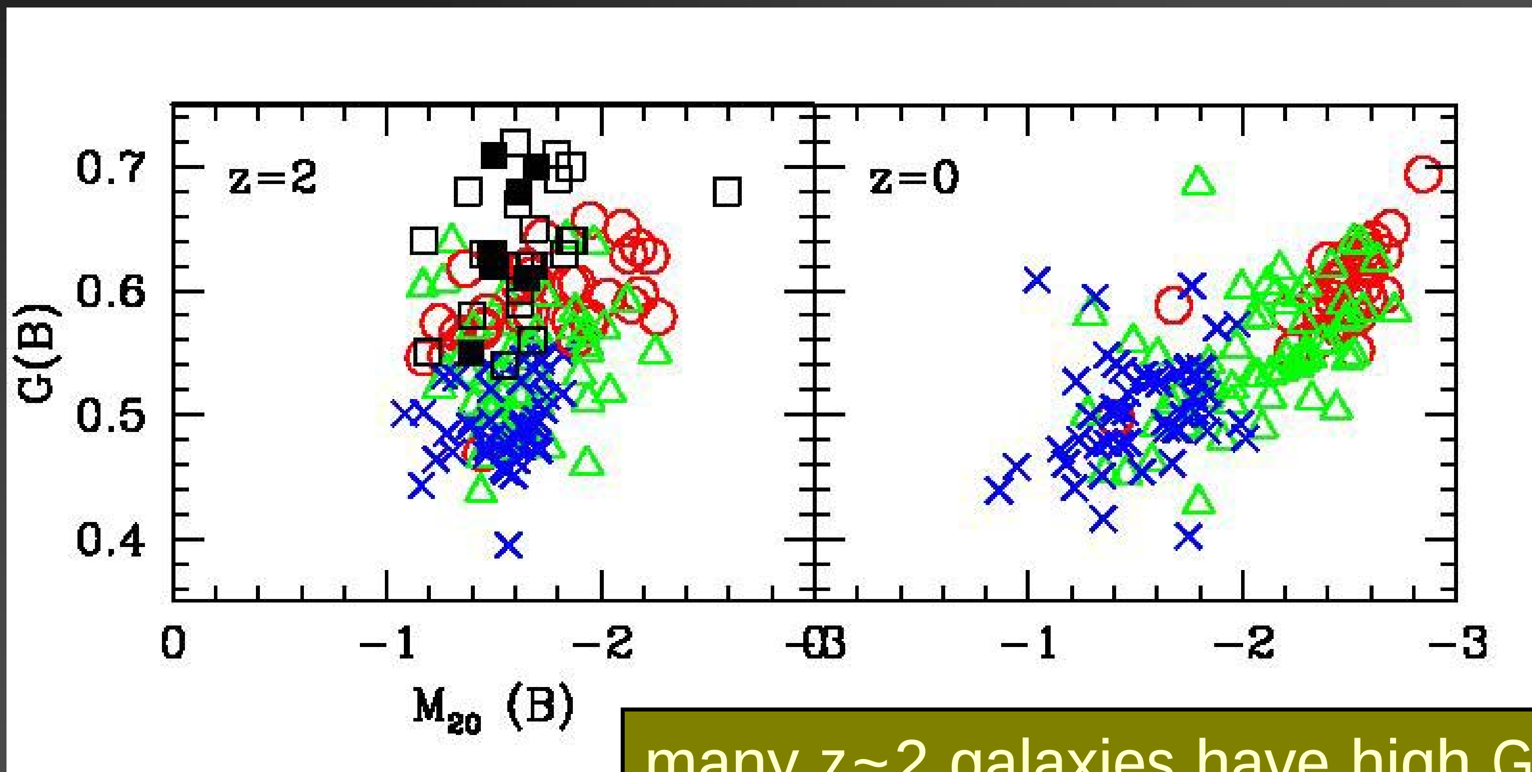
- tight sequence for “normal” galaxies
- most ULIRGs lie above this sequence

G-M_{20} vs C-A



Lyman break galaxy morphologies

- NICMOS HDFN z= 2-3 LBG sample (Dickinson et al)
  F110W+F160W (~3200-4500 AA rest-frame)



many z~2 galaxies have high G

Modeling Merger Morphologies

T.J. Cox's simulations of colliding disks (gas, stars, DM)
+ P. Jonsson's radiative transfer + pop. synthesis code

→ can predict merger morphologies + morph. evolution

will test merger mass ratios,
orbital parameters,
initial galaxy conditions (B/D, gas fraction, ...),
dust models

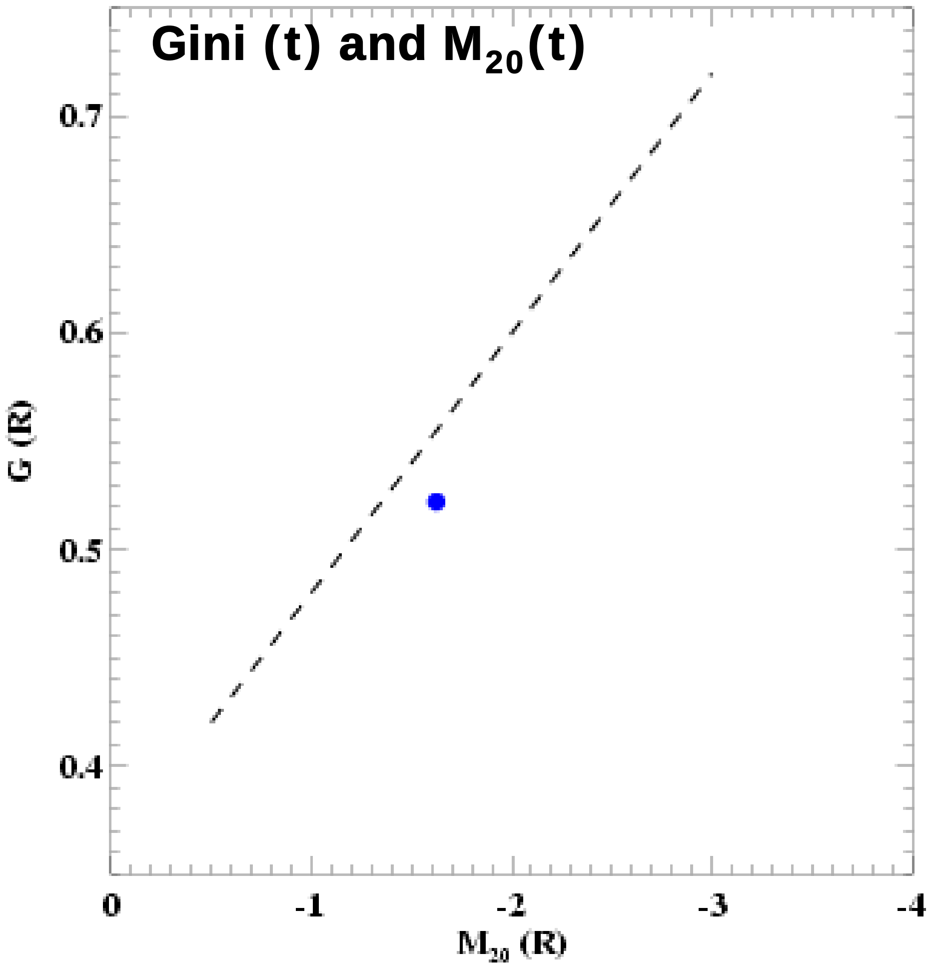
Modeling Merger Morphologies

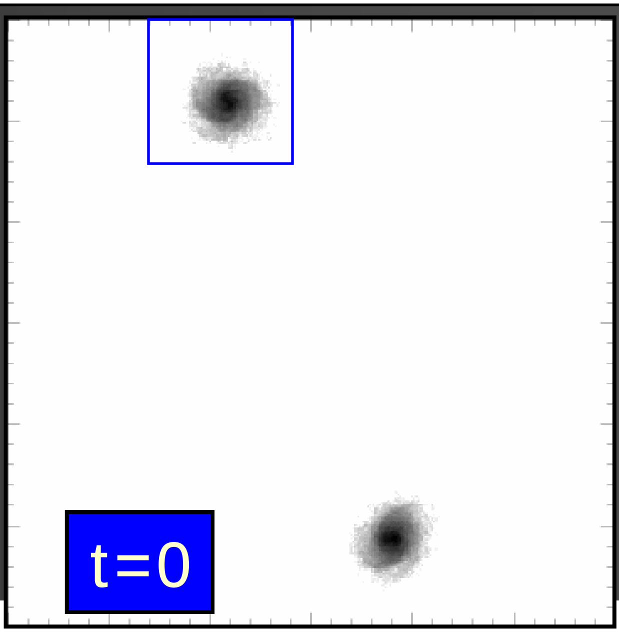
T.J. Cox's simulations of colliding disks (gas, stars, DM)
+ P. Jonsson's radiative transfer + pop. synthesis code

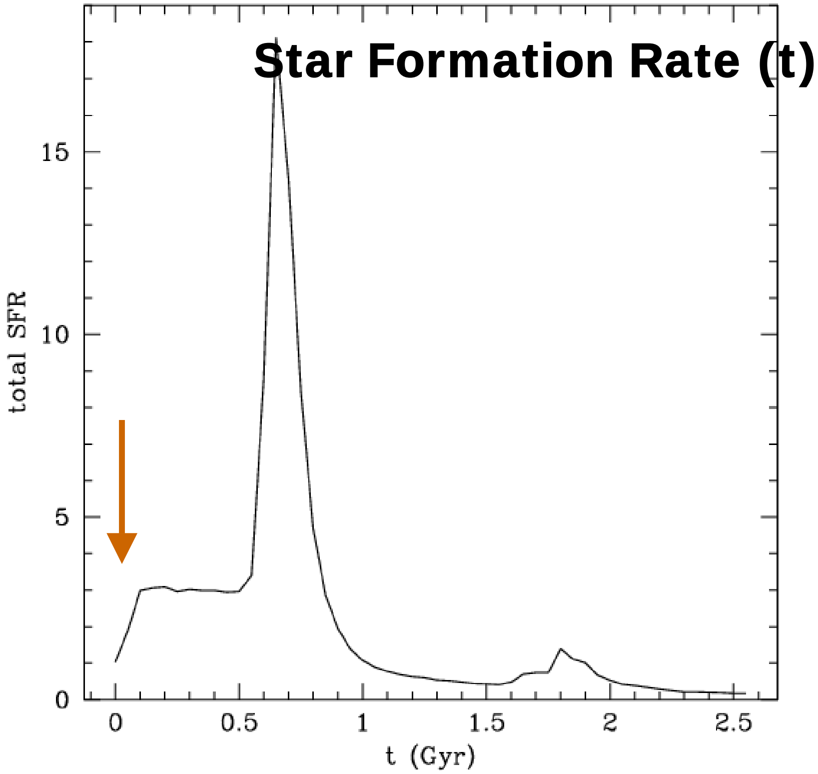
→ multi-wavelength images of simulations

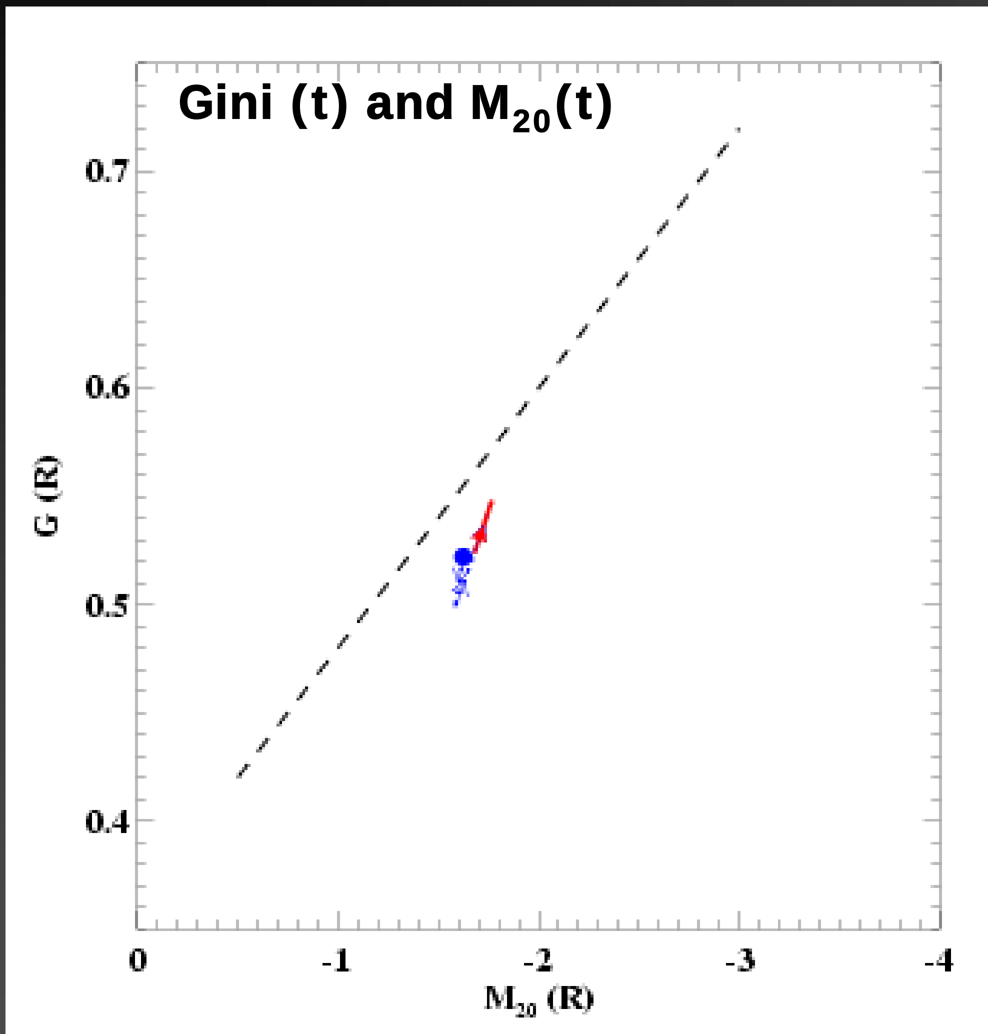
→ can predict merger morphologies + morph. evolution

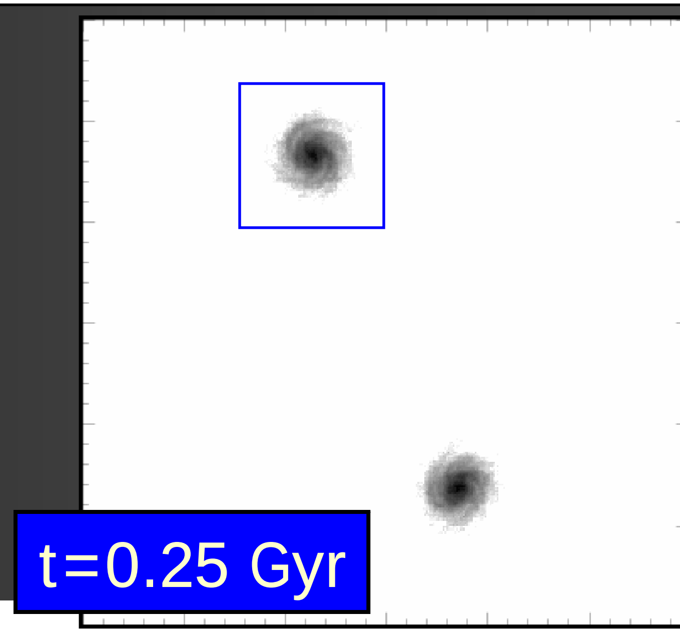
will test merger mass ratios,
orbital parameters,
initial galaxy conditions (B/D, gas fraction, …),
dust models

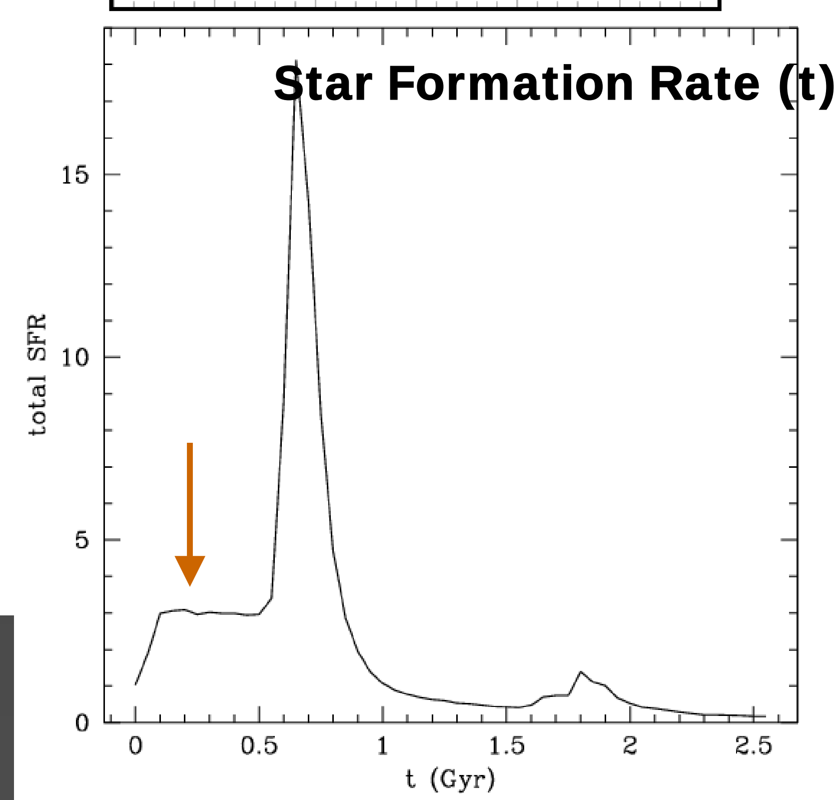

Gini (t) and M_{20}(t)
0.7
0.6
0.5
0.4
G (R)
0
-1
-2
-3
-4
M_{20} (R)

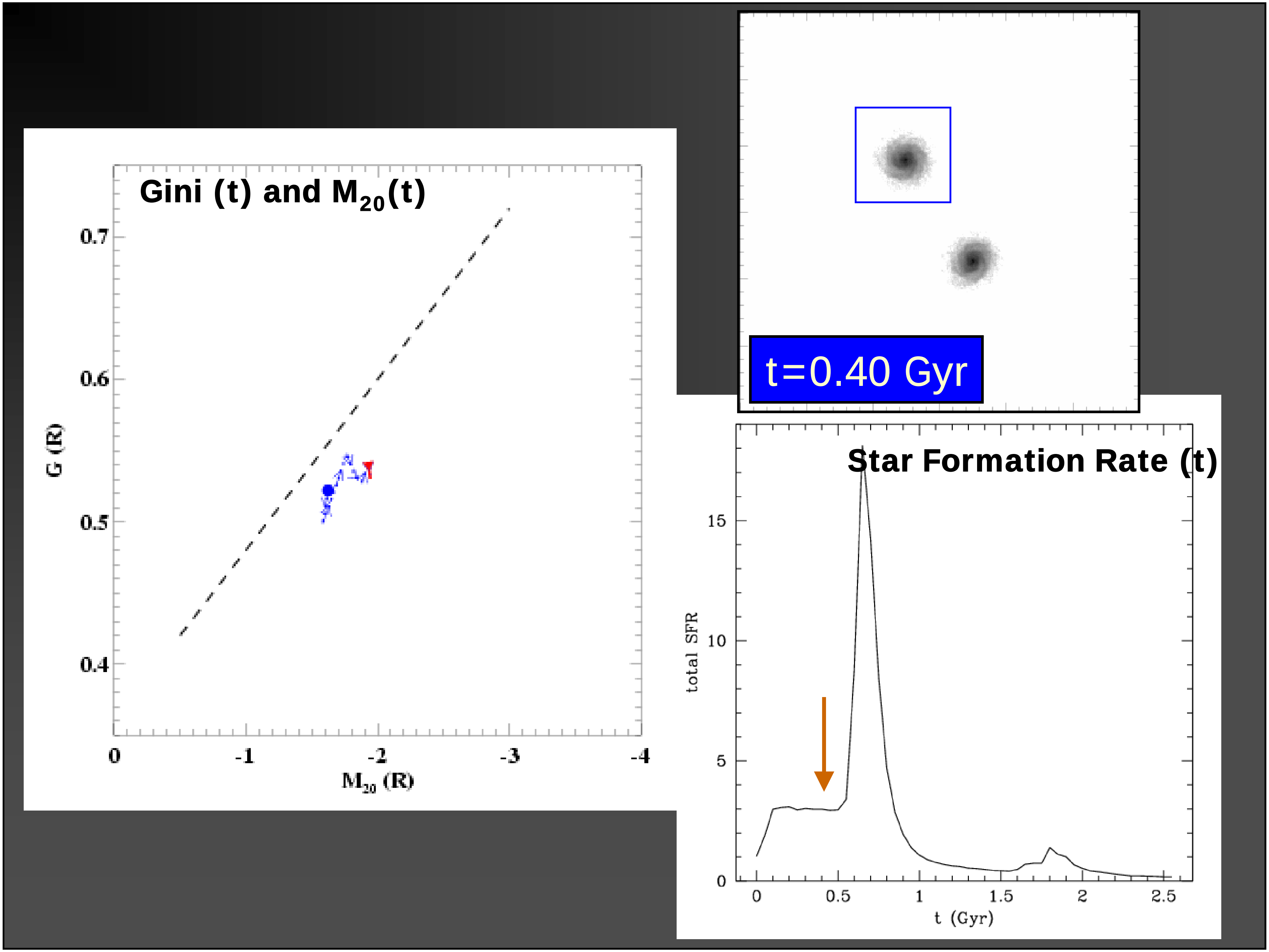

t=0


Star Formation Rate (t)
total SFR
0
5
10
15
0
0.5
1
1.5
2
2.5
t (Gyr)


Gini (t) and M_{20}(t)
0.7
0.6
0.5
0.4
G (R)
0
-1
-2
-3
-4
M_{20} (R)

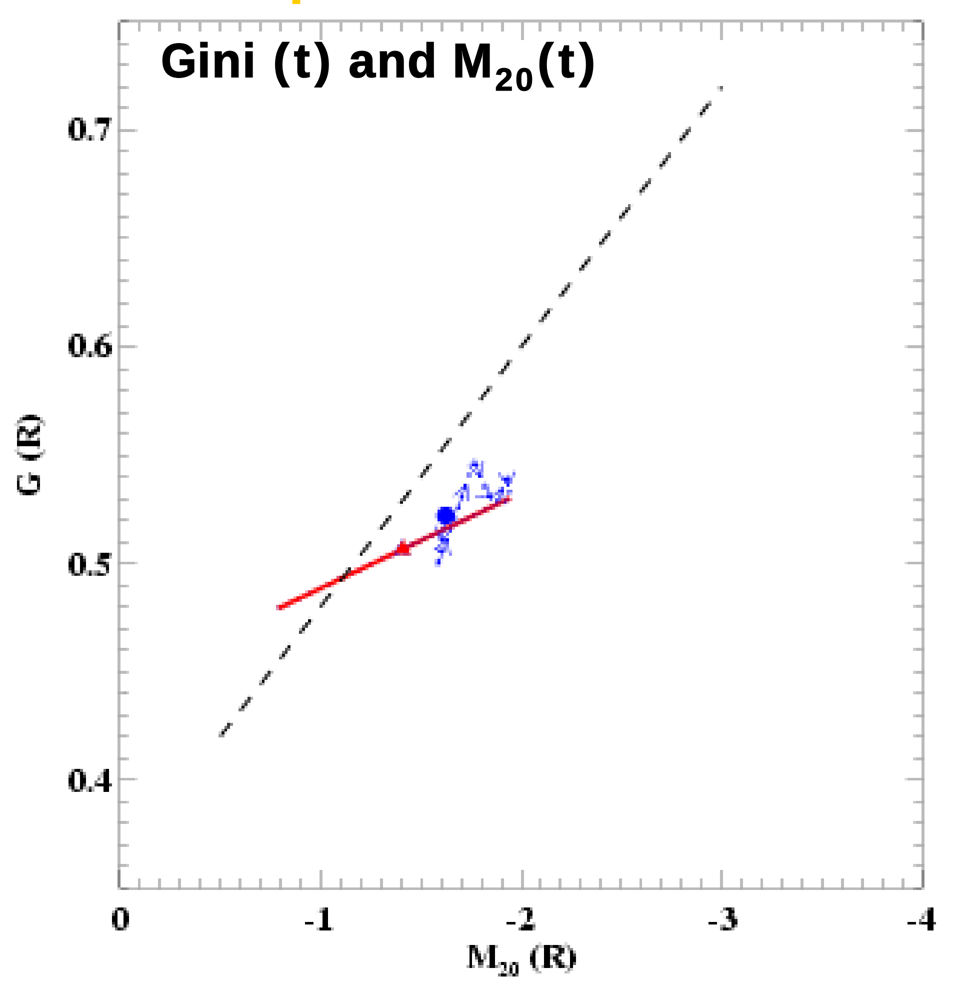

t=0.25 Gyr


Star Formation Rate (t)
15
10
5
0
total SFR
0
0.5
1
1.5
2
2.5
t (Gyr)

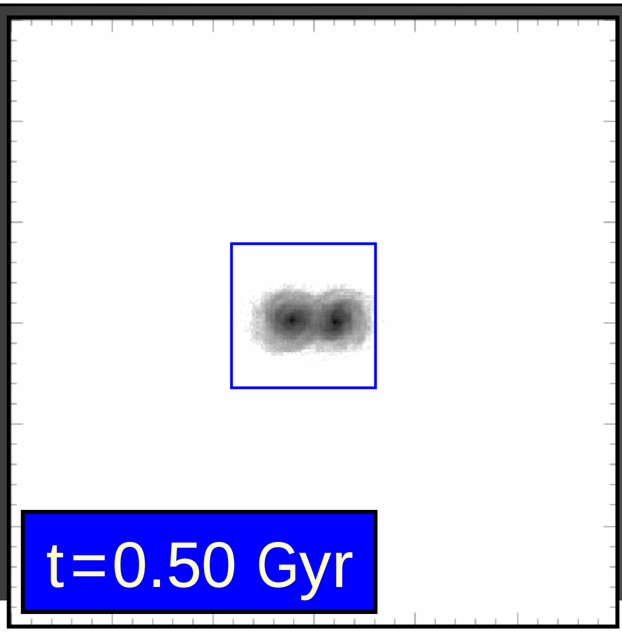


Gini (t) and M_{20}(t)
G (R)
M_{20} (R)
0.7
0.6
0.5
0.4
0
-1
-2
-3
-4
t=0.40 Gyr
Star Formation Rate (t)
total SFR
t (Gyr)
15
10
5
0
0.5
1
1.5
2
2.5

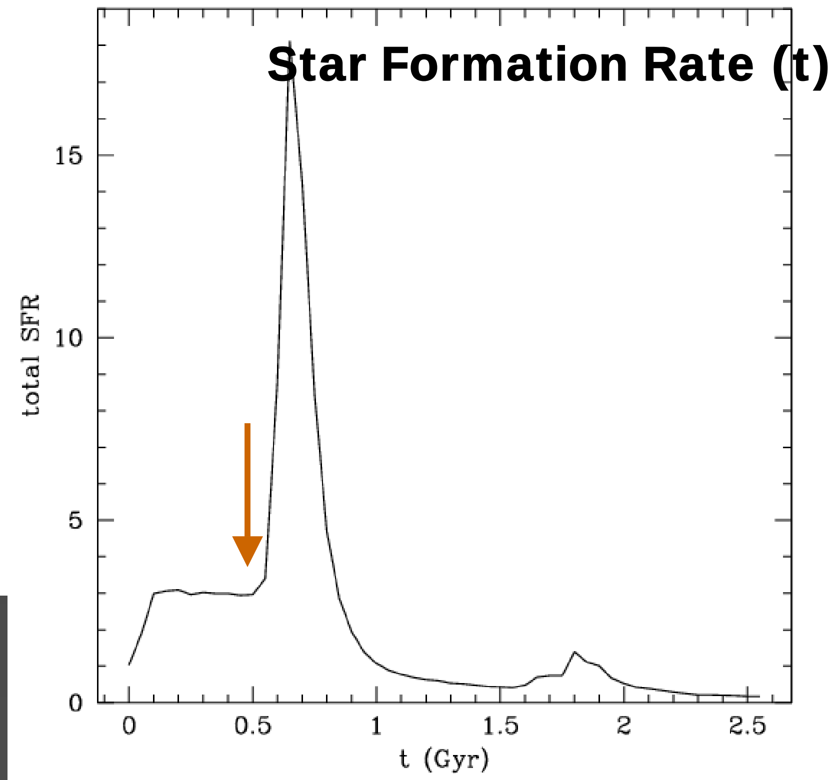
first pass



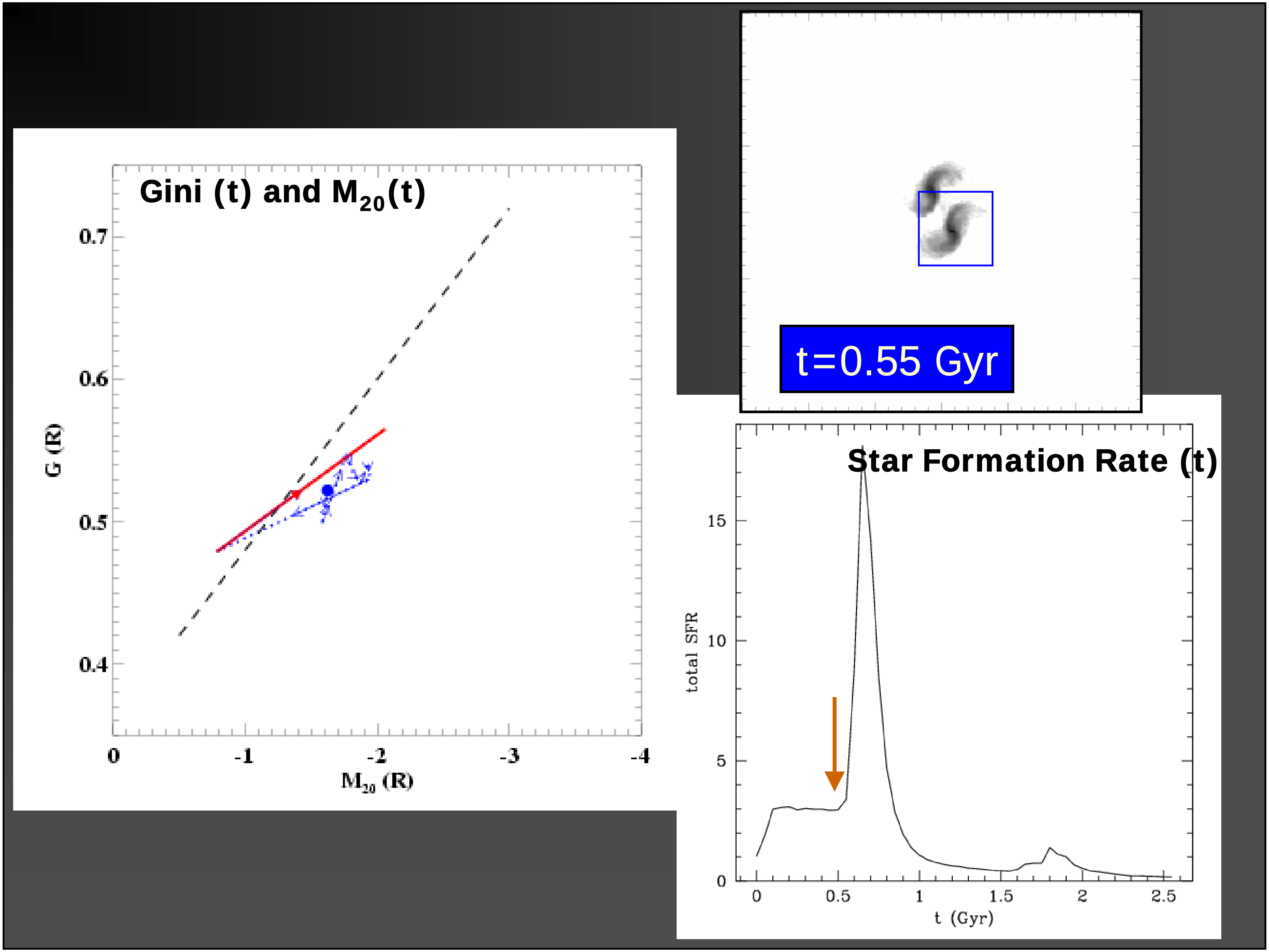
Gini (t) and M_{20}(t)
0.7
0.6
0.5
0.4
G (R)
0
-1
-2
-3
-4
M_{20} (R)

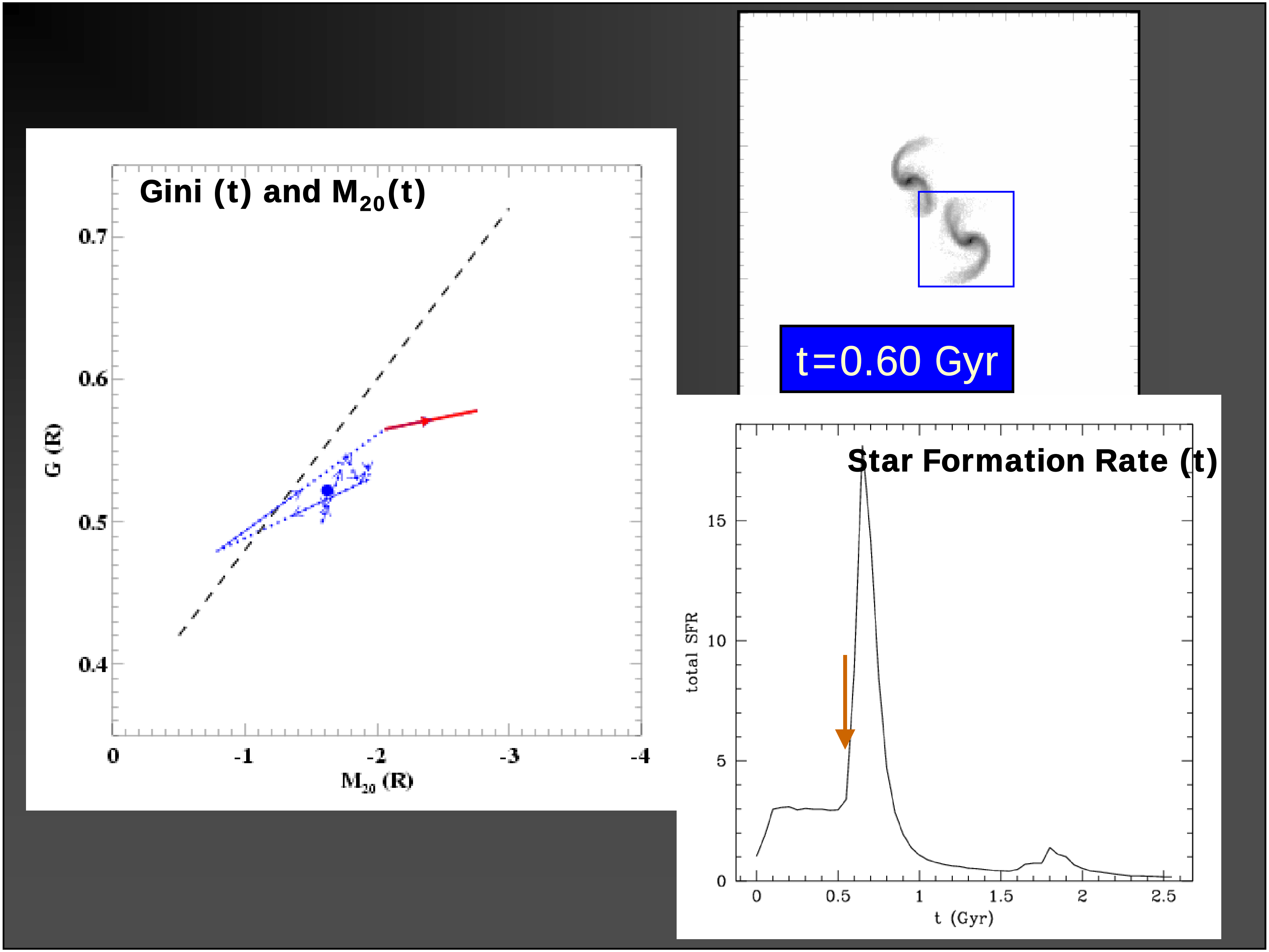


t=0.50 Gyr

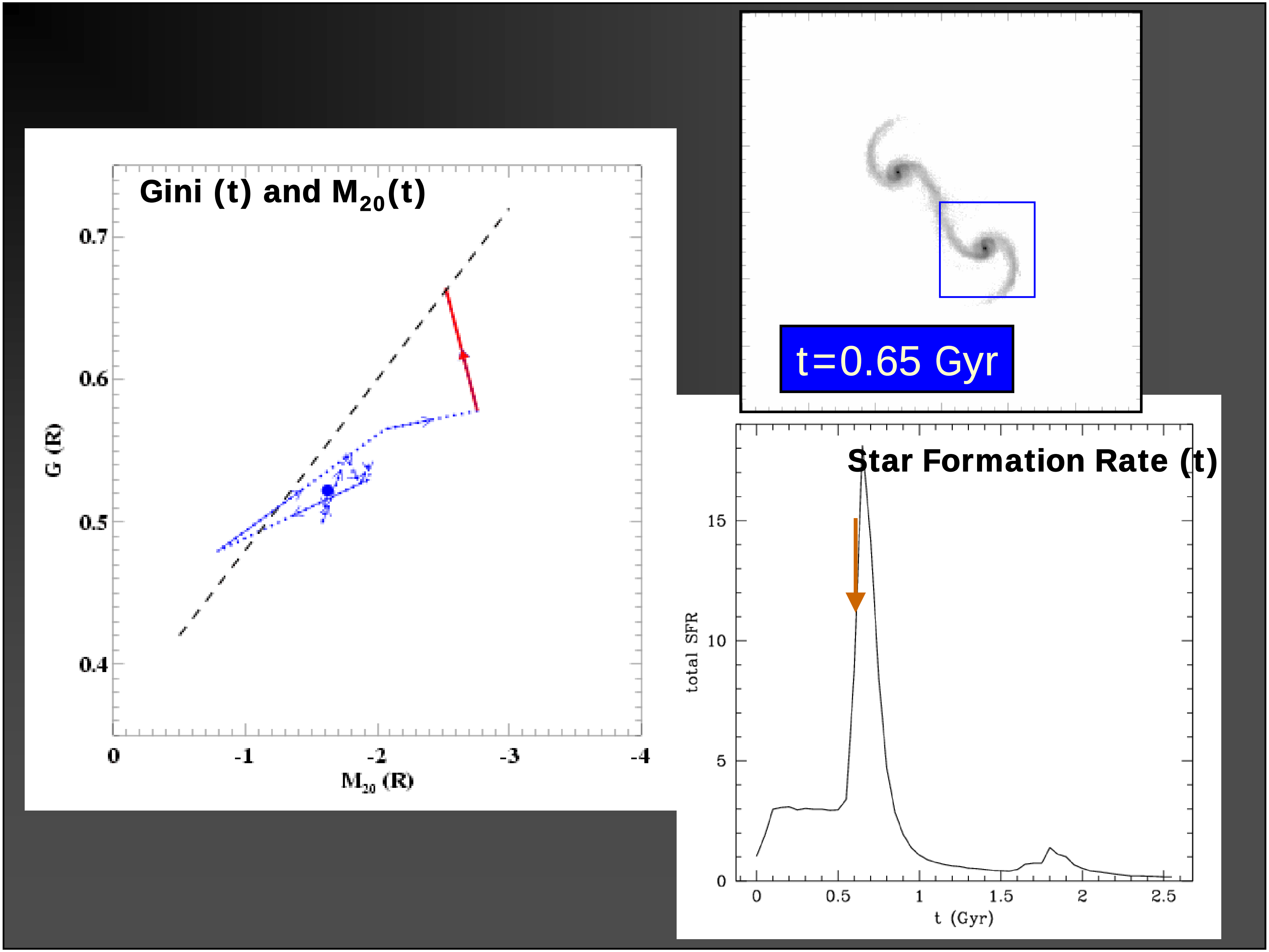


Star Formation Rate (t)
15
10
5
0
total SFR
0
0.5
1
1.5
2
2.5
t (Gyr)

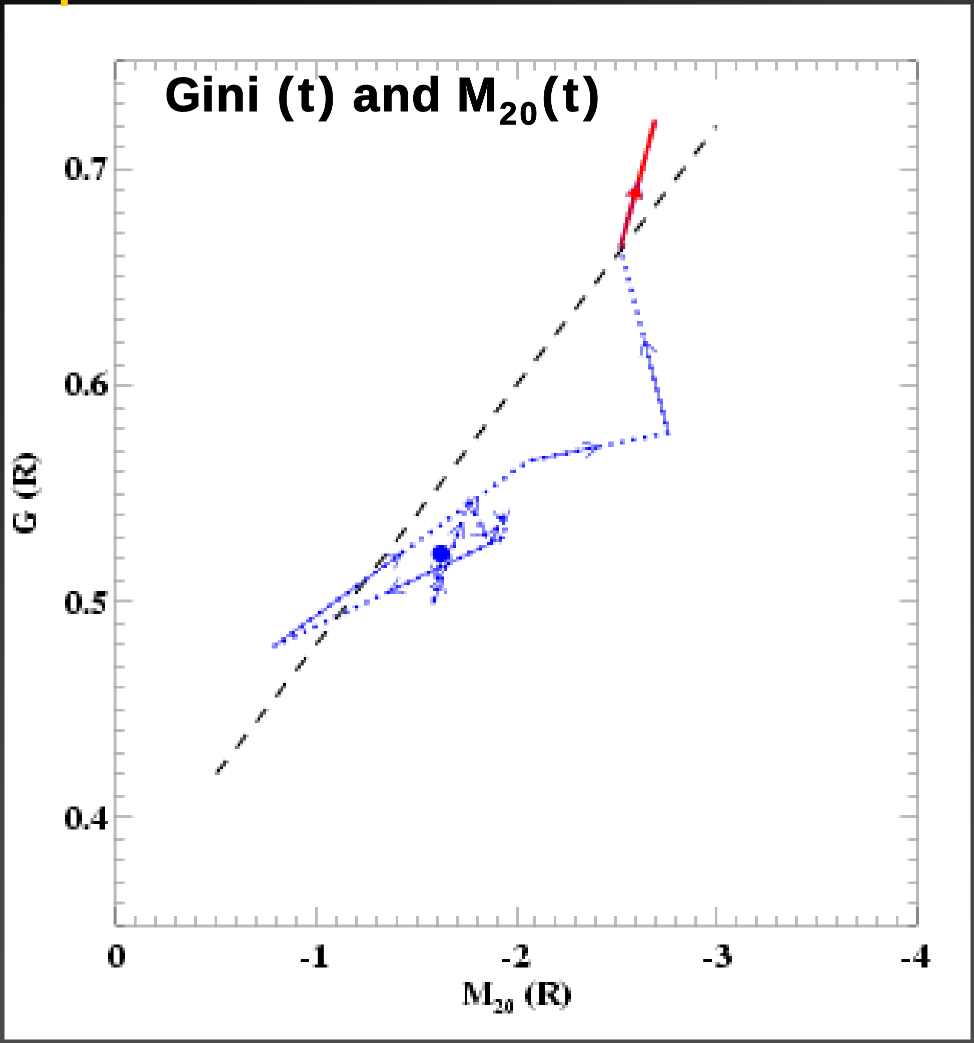

Gini (t) and M_{20}(t)
G (R)
0.7
0.6
0.5
0.4
0
-1
-2
-3
-4
M_{20} (R)
t=0.55 Gyr
Star Formation Rate (t)
total SFR
15
10
5
0
0
0.5
1
1.5
2
2.5
t (Gyr)

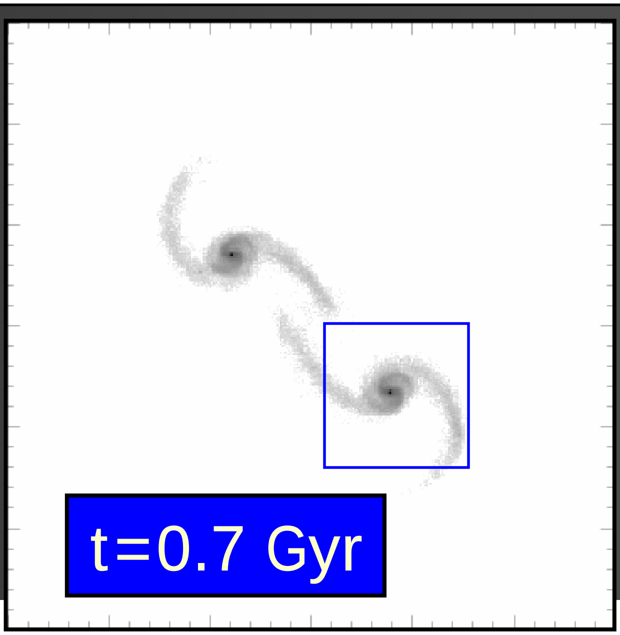


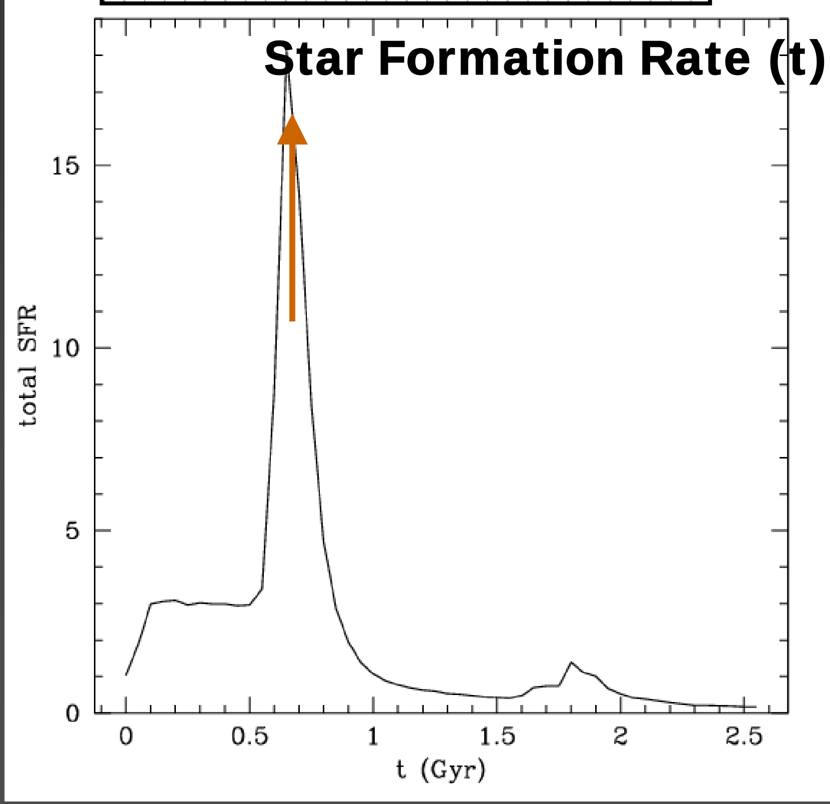
Gini (t) and M_{20}(t)
0.7
0.6
0.5
0.4
G (R)
0
-1
-2
-3
-4
M_{20} (R)
t=0.60 Gyr
Star Formation Rate (t)
15
10
5
0
total SFR
0
0.5
1
1.5
2
2.5
t (Gyr)

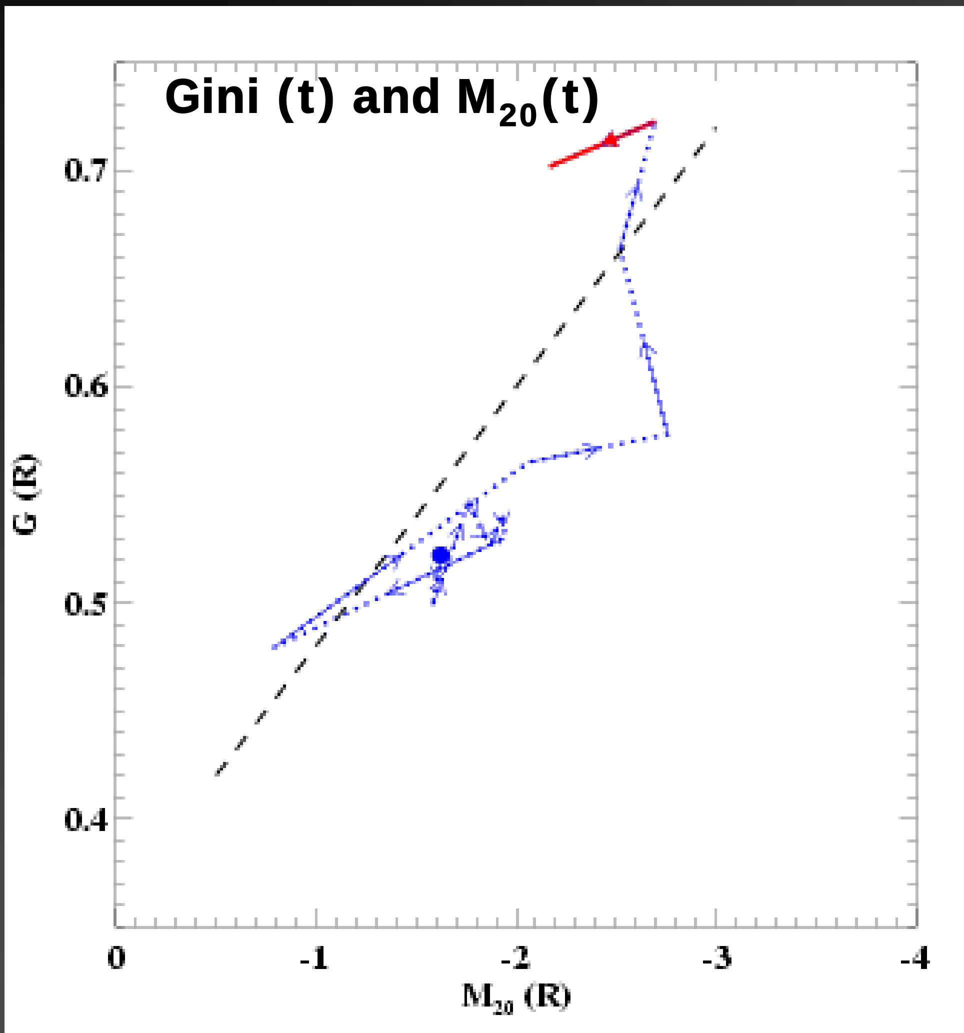

Gini (t) and M_{20}(t)
0.7
0.6
0.5
0.4
G (R)
0
-1
-2
-3
-4
M_{20} (R)
t=0.65 Gyr
Star Formation Rate (t)
15
10
5
0
total SFR
0
0.5
1
1.5
2
2.5
t (Gyr)

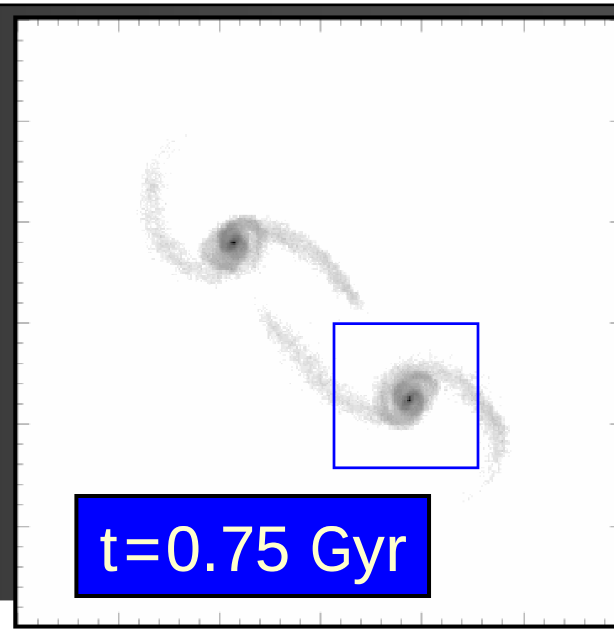
peak in star formation

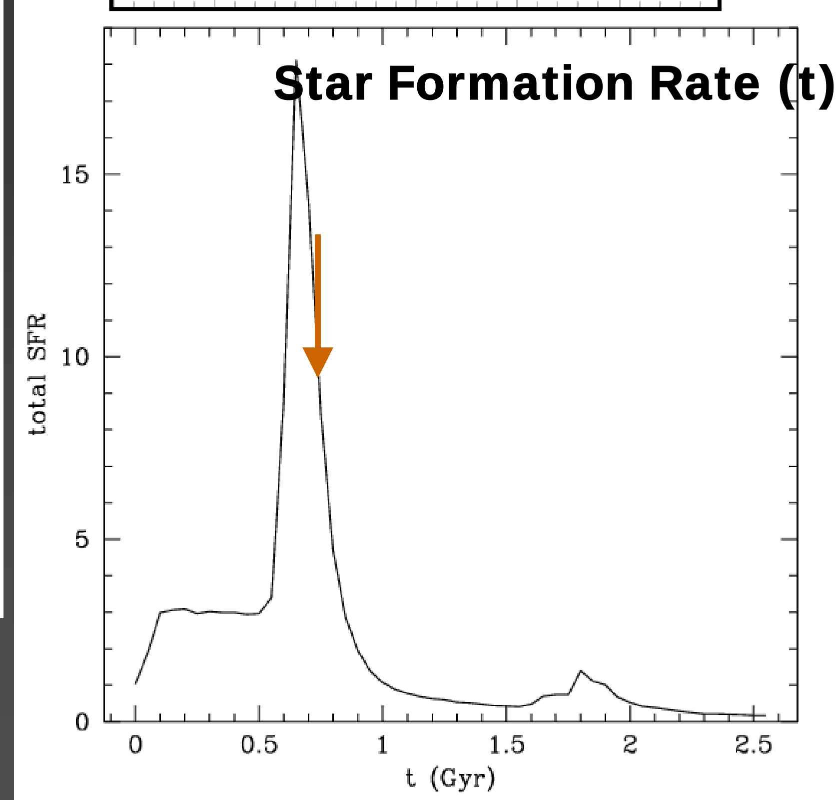


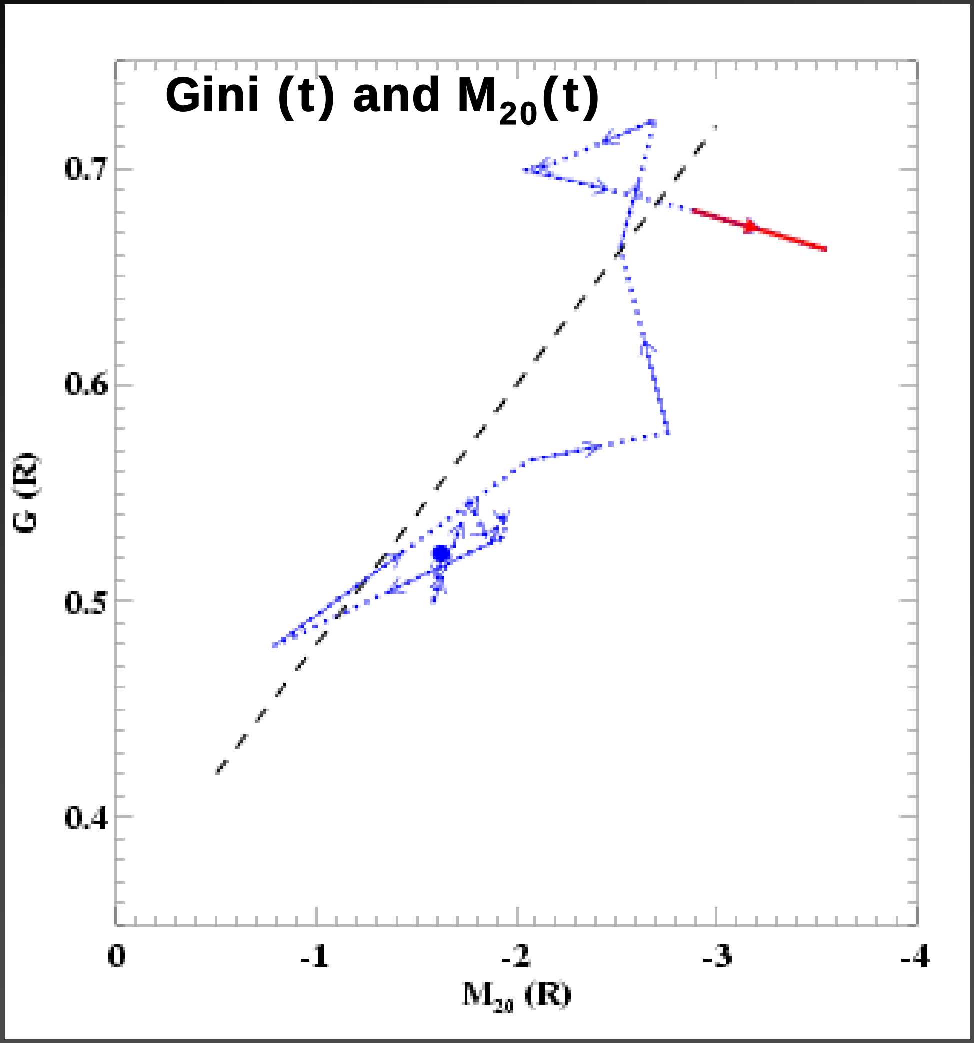


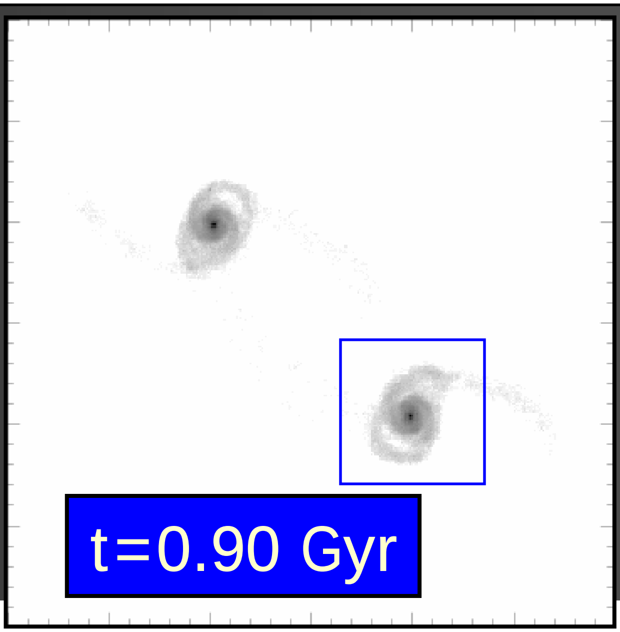


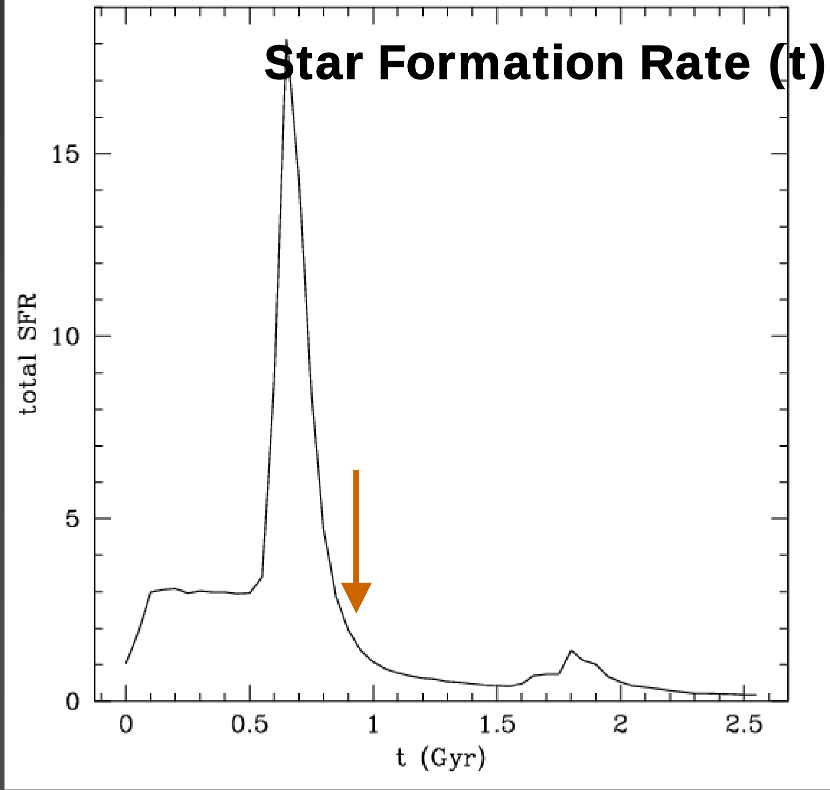

Gini (t) and M_{20}(t)
0.7
0.6
0.5
0.4
G (R)
0
-1
-2
-3
-4
M_{20} (R)

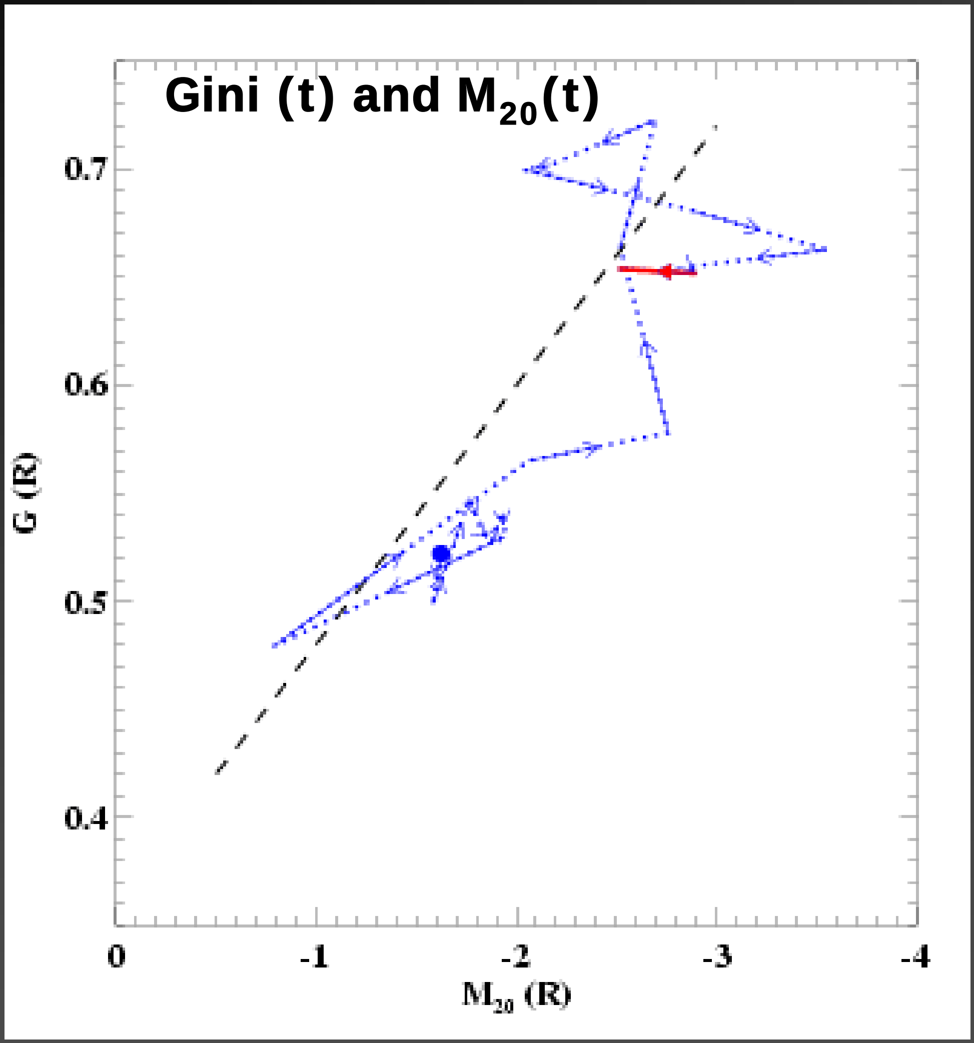

t=0.75 Gyr

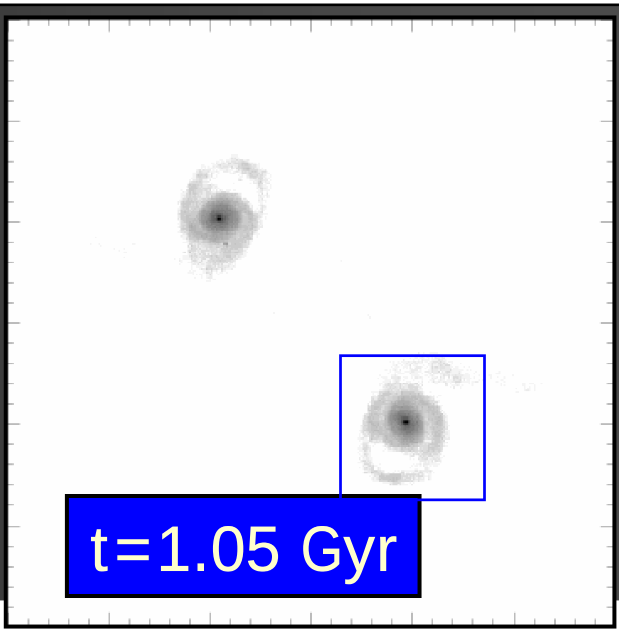

Star Formation Rate (t)
15
10
5
0
total SFR
0
0.5
1
1.5
2
2.5
t (Gyr)

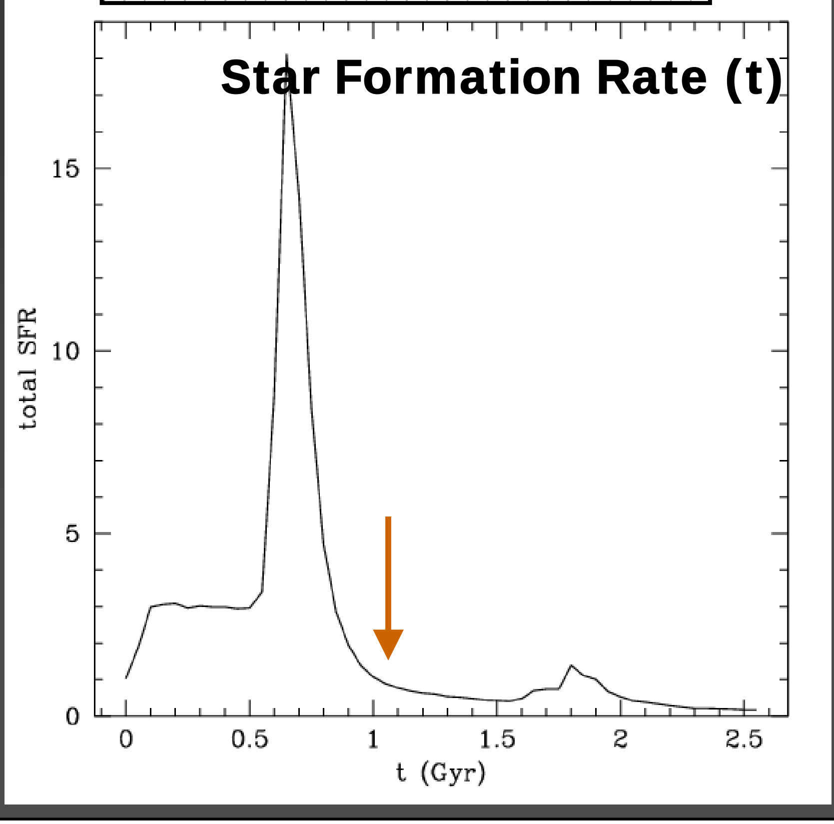

Gini (t) and M_{20}(t)
0.7
0.6
0.5
0.4
G (R)
0
-1
-2
-3
-4
M_{20} (R)

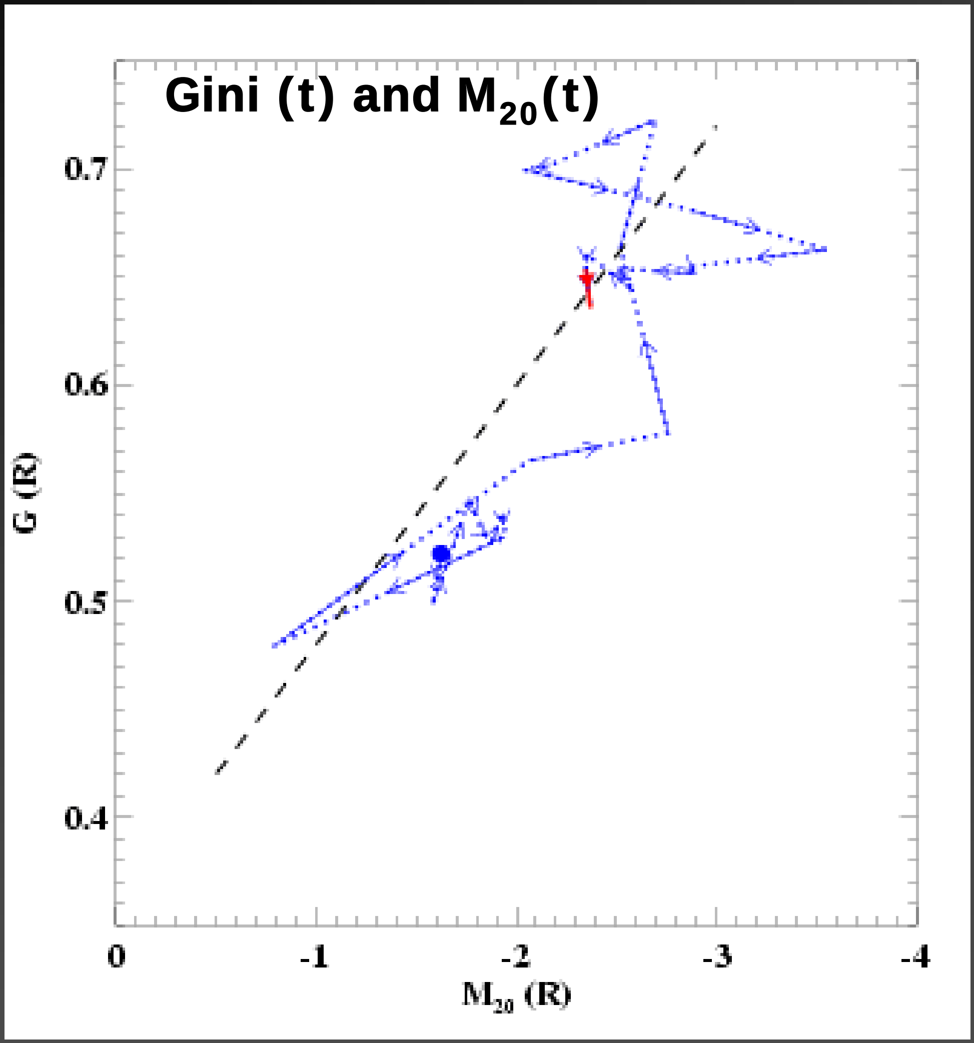

t=0.90 Gyr

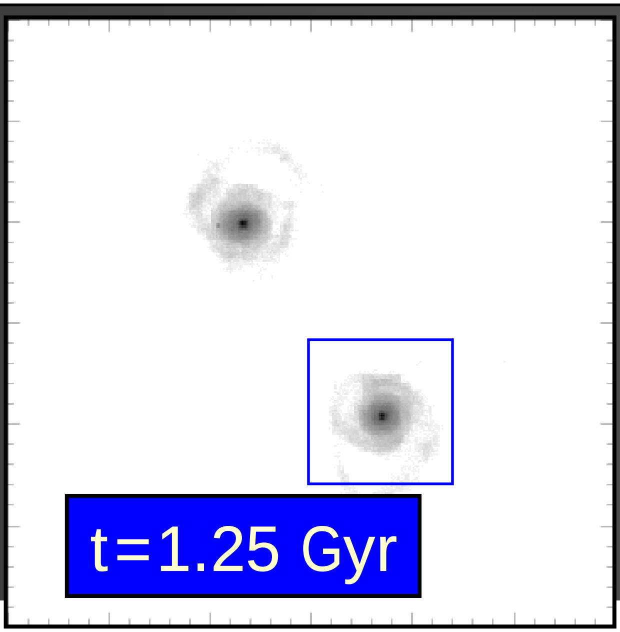

Star Formation Rate (t)
15
10
5
0
total SFR
0
0.5
1
1.5
2
2.5
t (Gyr)

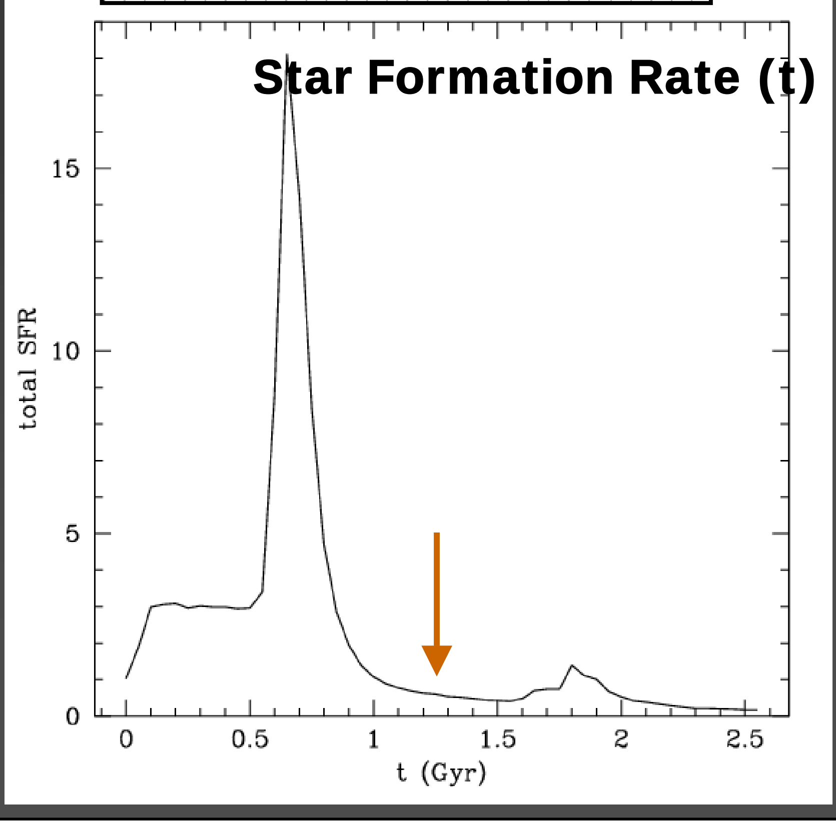

Gini (t) and M_{20}(t)
G (R)
M_{20} (R)
0.7
0.6
0.5
0.4
0
-1
-2
-3
-4

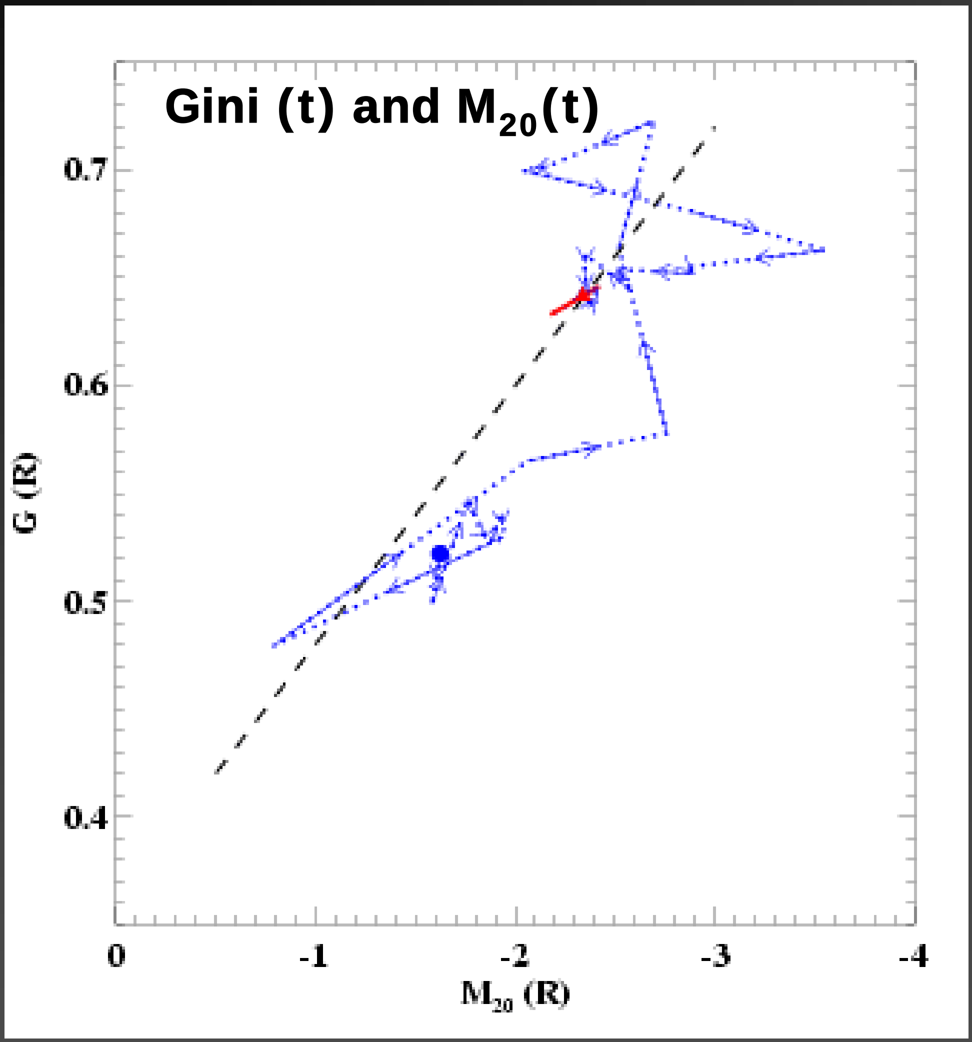

t=1.05 Gyr


Star Formation Rate (t)
total SFR
t (Gyr)
0
5
10
15
0
0.5
1
1.5
2
2.5

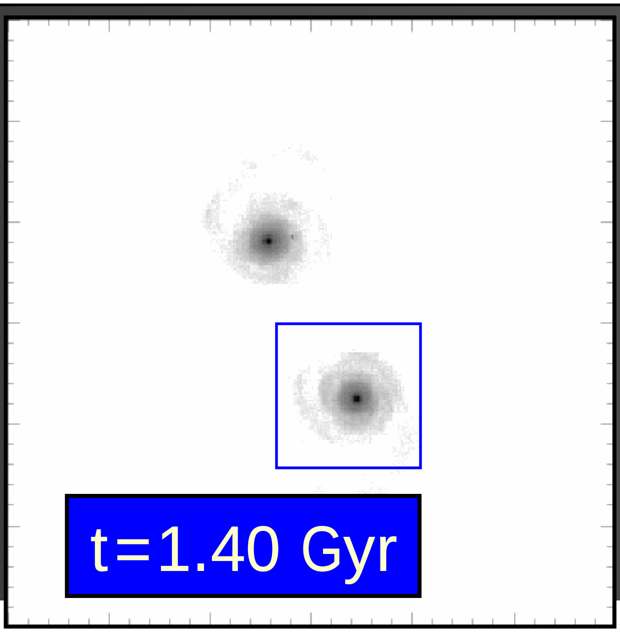

Gini (t) and M_{20}(t)
0.7
0.6
0.5
0.4
G (R)
0
-1
-2
-3
-4
M_{20} (R)


t=1.25 Gyr

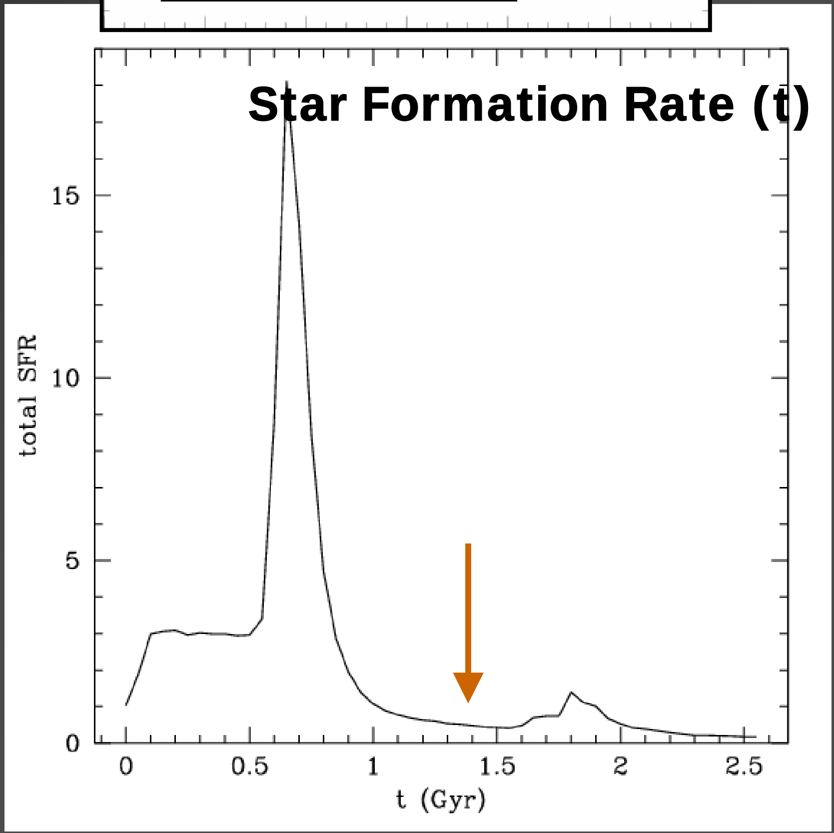

Star Formation Rate (t)
15
10
5
0
total SFR
0
0.5
1
1.5
2
2.5
t (Gyr)



Gini (t) and M_{20}(t)
0.7
0.6
0.5
0.4
G (R)
0
-1
-2
-3
-4
M_{20} (R)

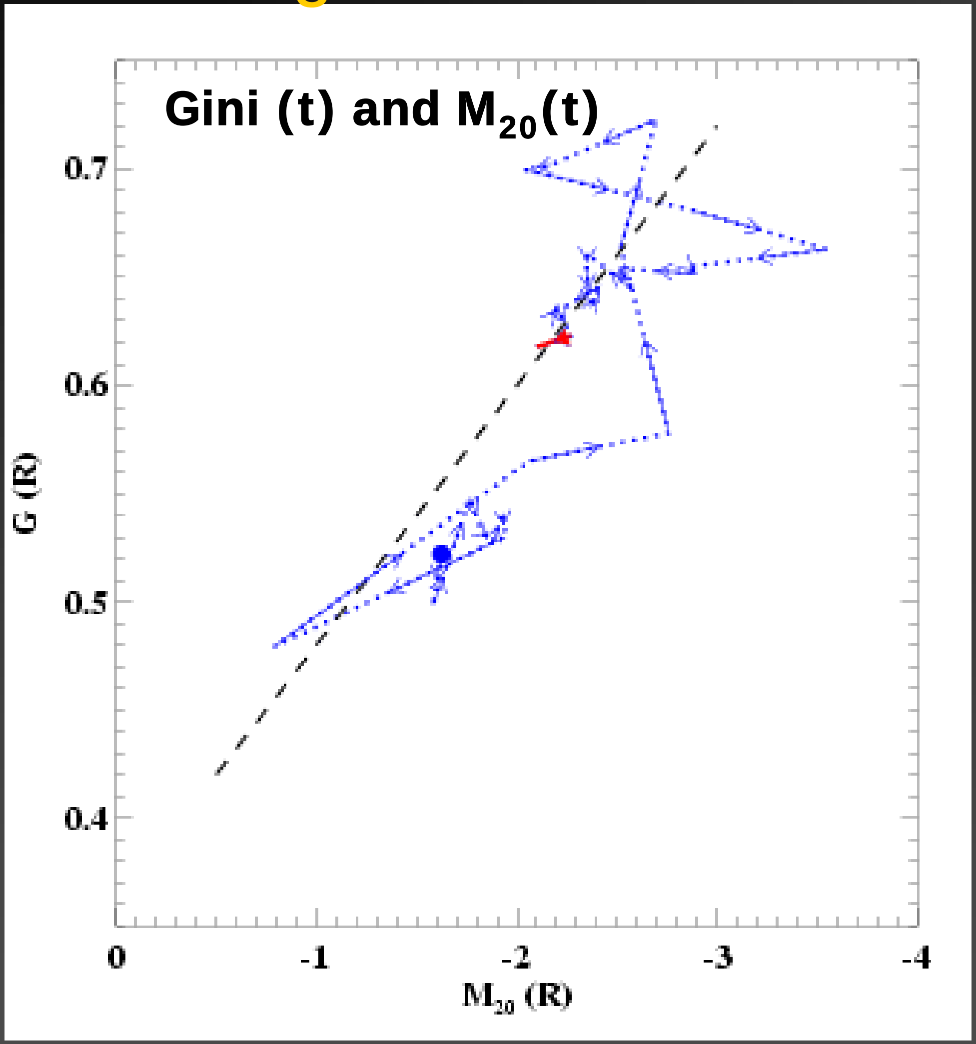


t=1.40 Gyr

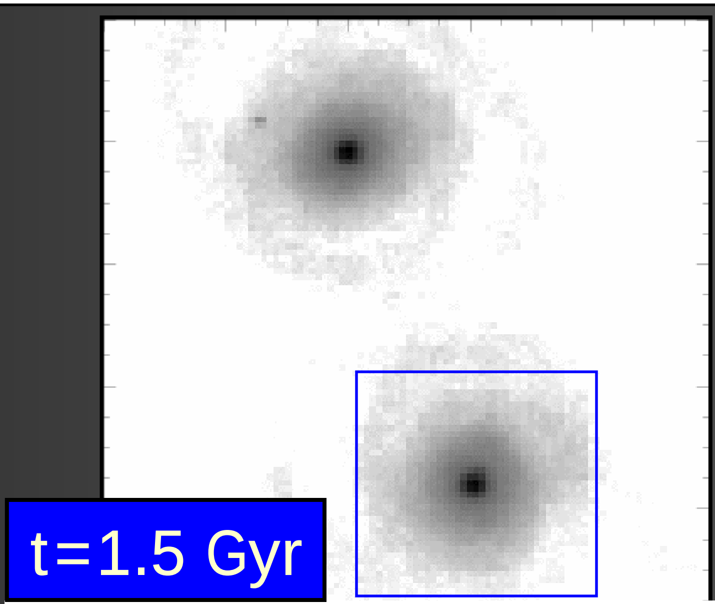


Star Formation Rate (t)
15
10
5
0
total SFR
0
0.5
1
1.5
2
2.5
t (Gyr)

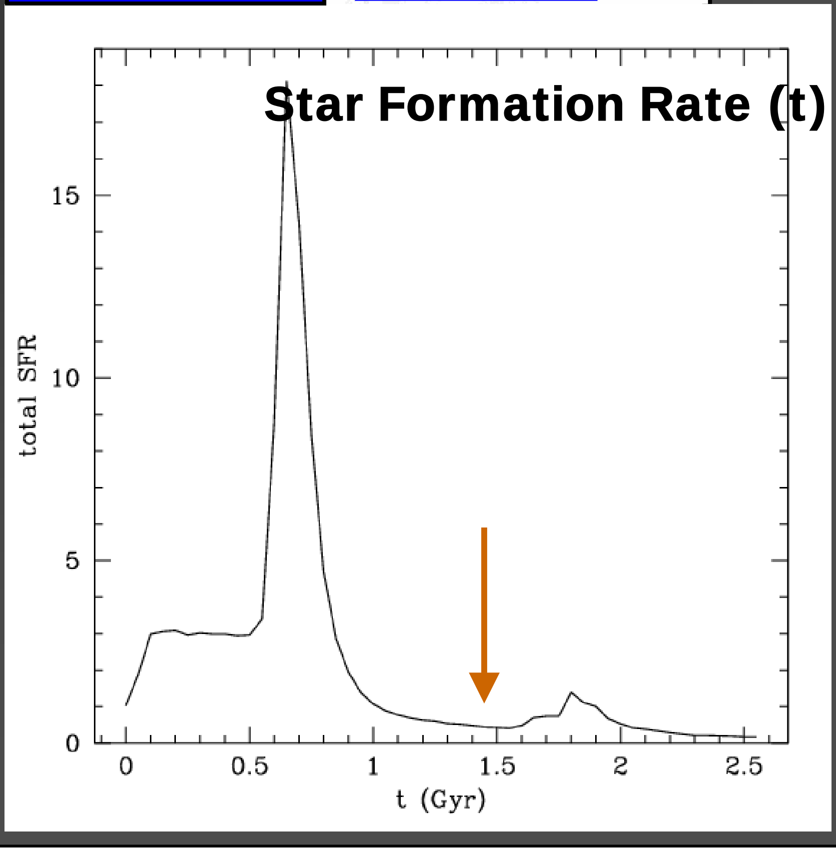
zooming in ...



Gini (t) and M_{20}(t)
0.7
0.6
0.5
0.4
G (R)
0
-1
-2
-3
-4
M_{20} (R)

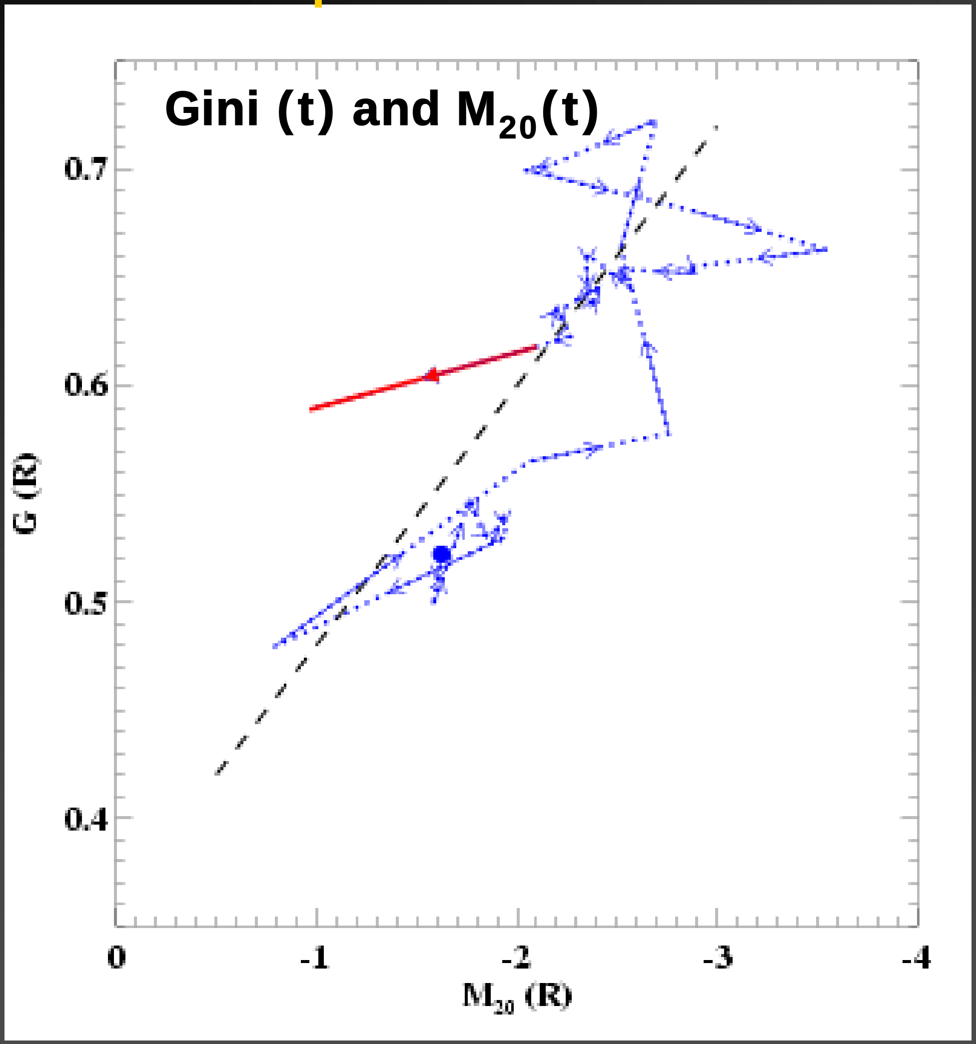


t=1.5 Gyr

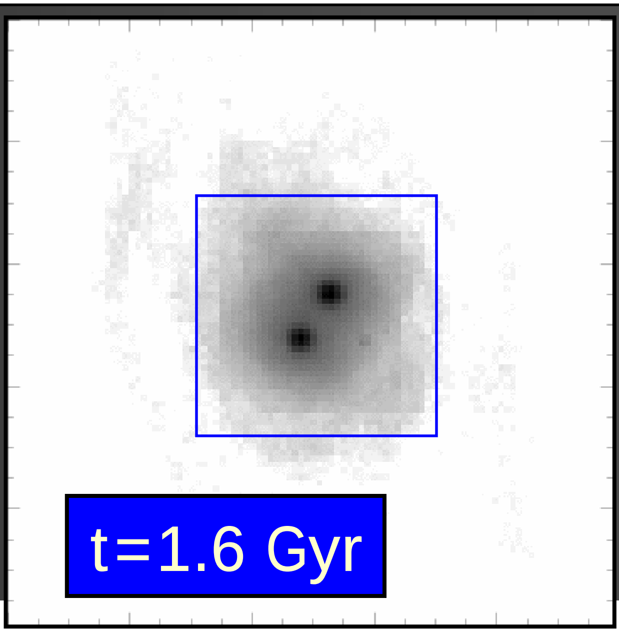


Star Formation Rate (t)
total SFR
0
5
10
15
0
0.5
1
1.5
2
2.5
t (Gyr)

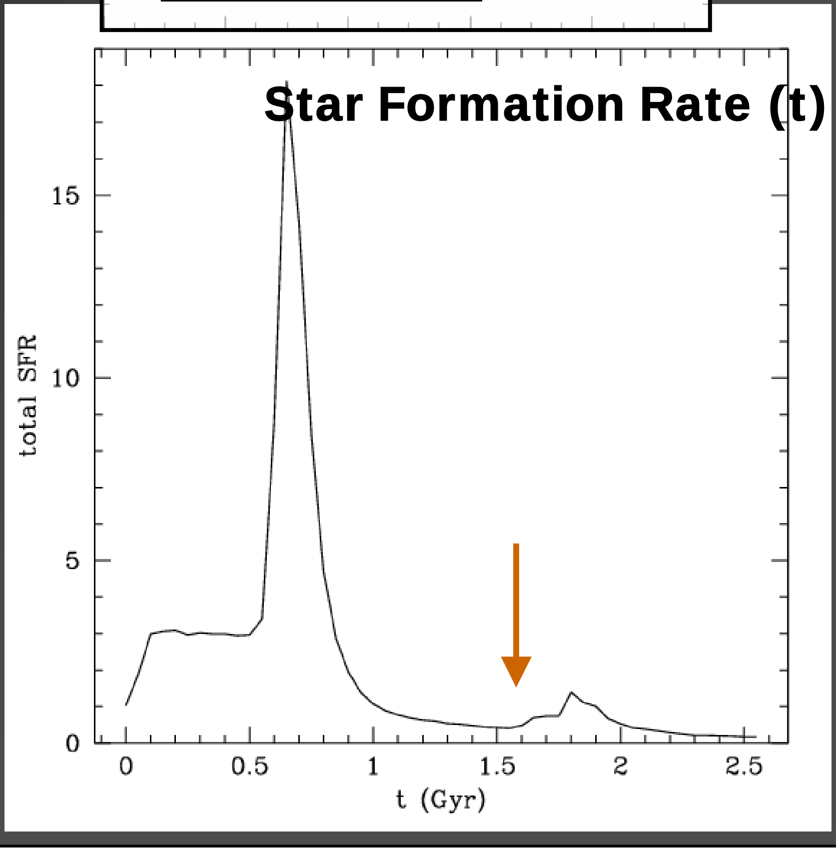
second pass



Gini (t) and M_{20}(t)
0.7
0.6
0.5
0.4
G (R)
0
-1
-2
-3
-4
M_{20} (R)

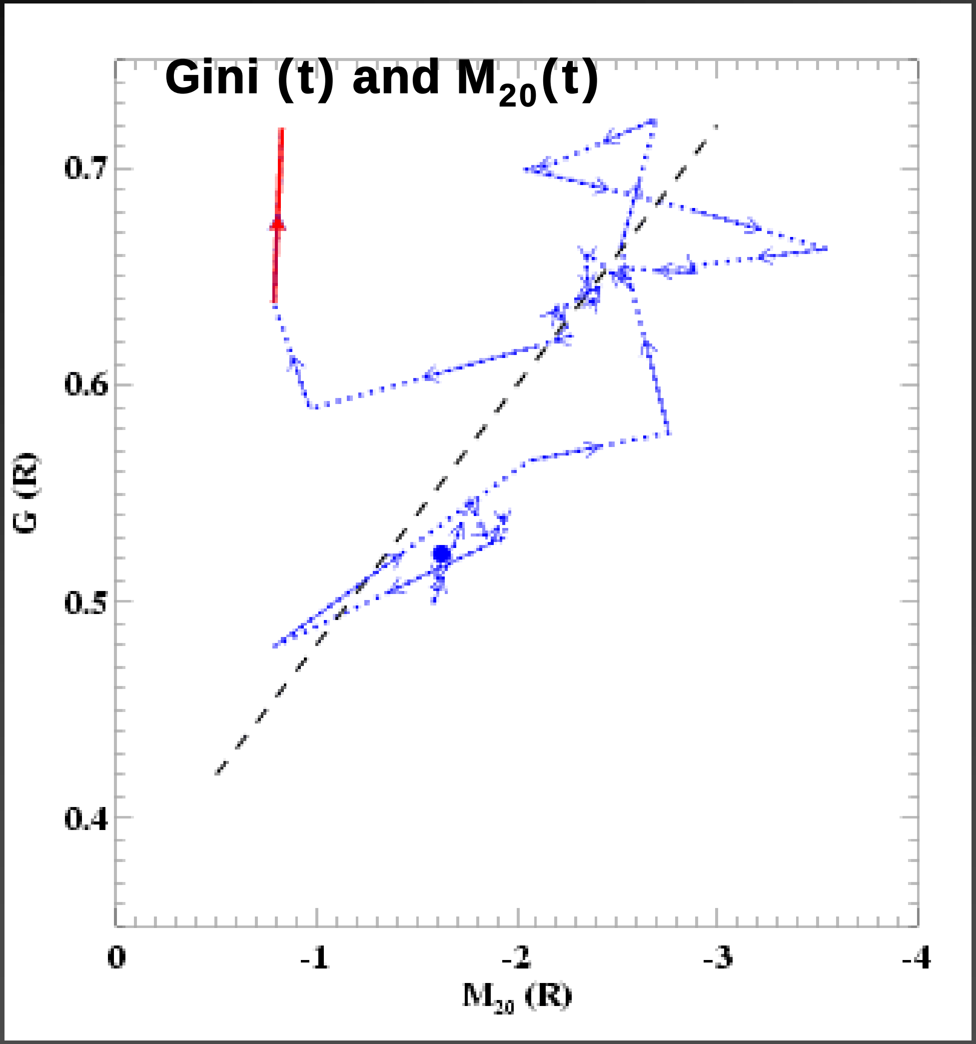


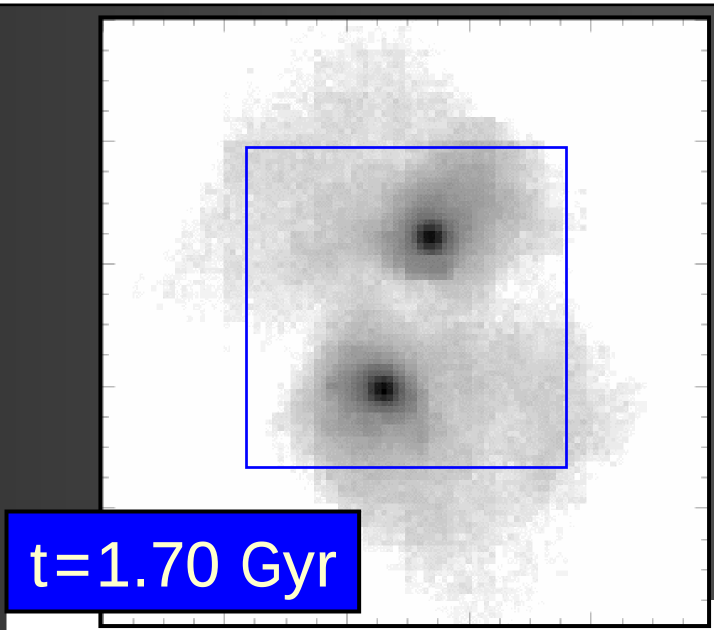
t=1.6 Gyr

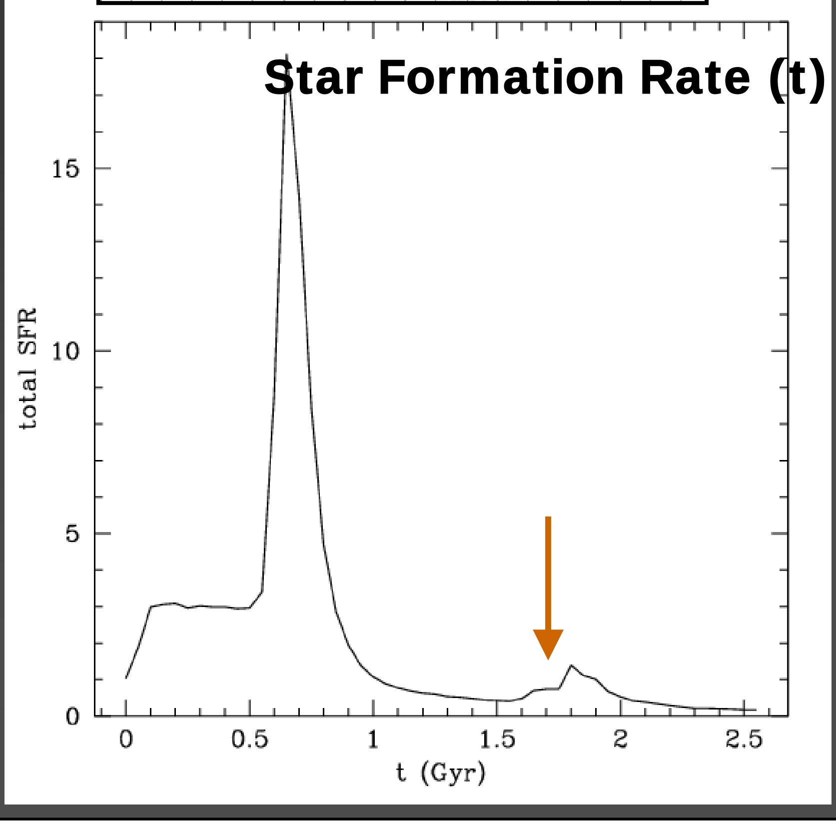


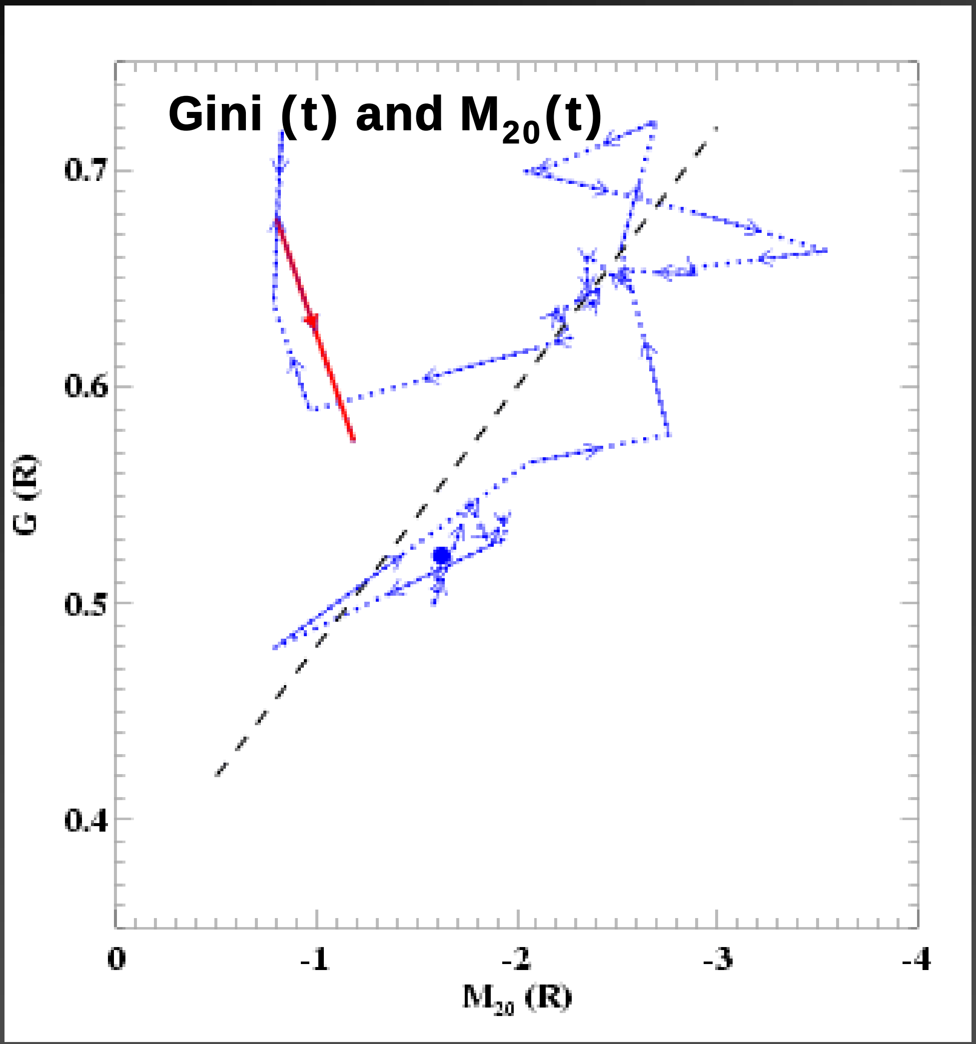
Star Formation Rate (t)
total SFR
0
5
10
15
0
0.5
1
1.5
2
2.5
t (Gyr)

last star-burst

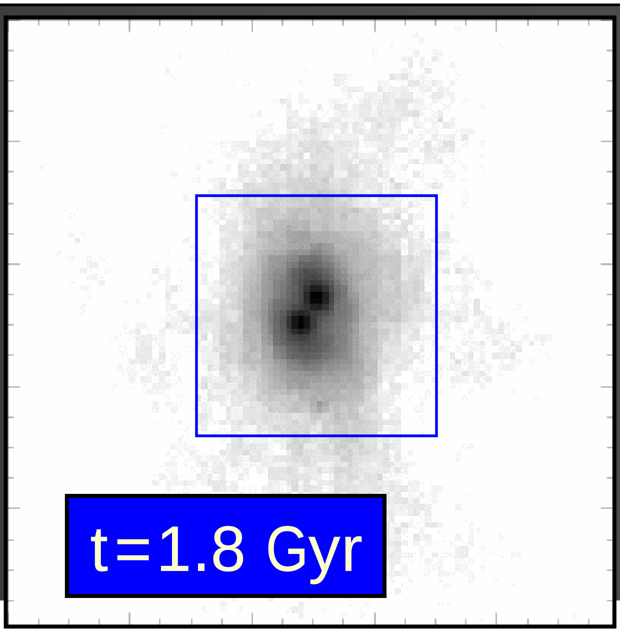




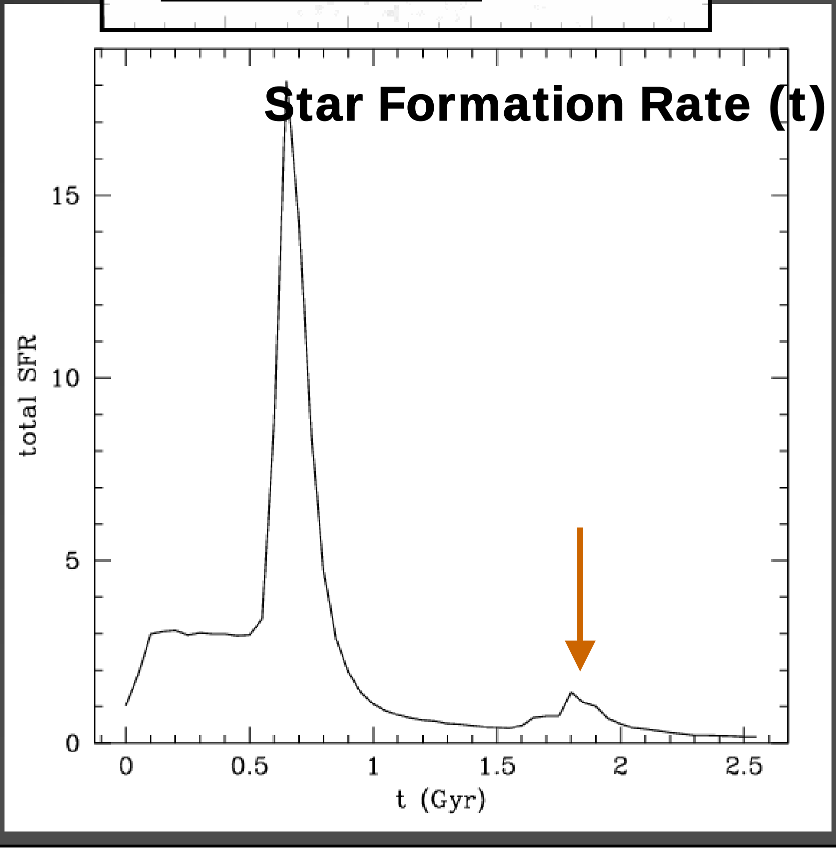




Gini (t) and M_{20}(t)
0.7
0.6
0.5
0.4
G (R)
0
-1
-2
-3
-4
M_{20} (R)

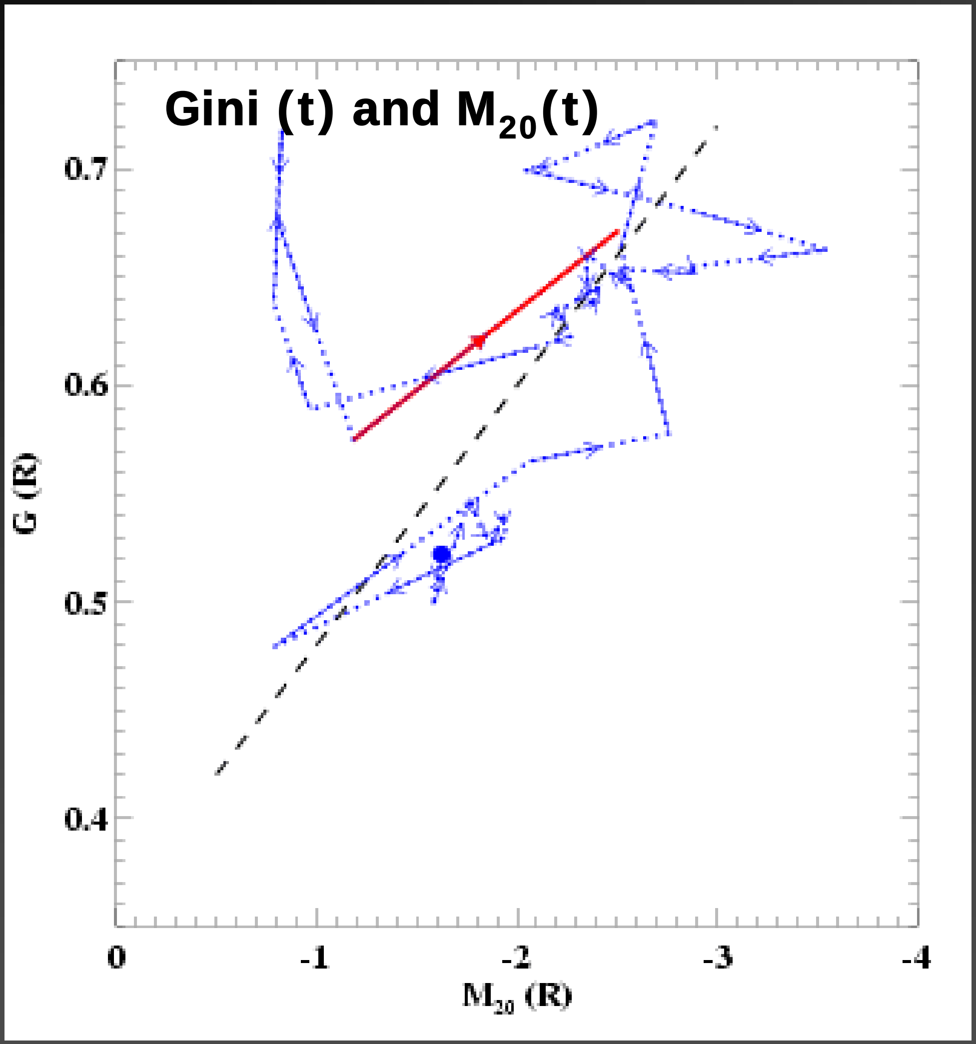


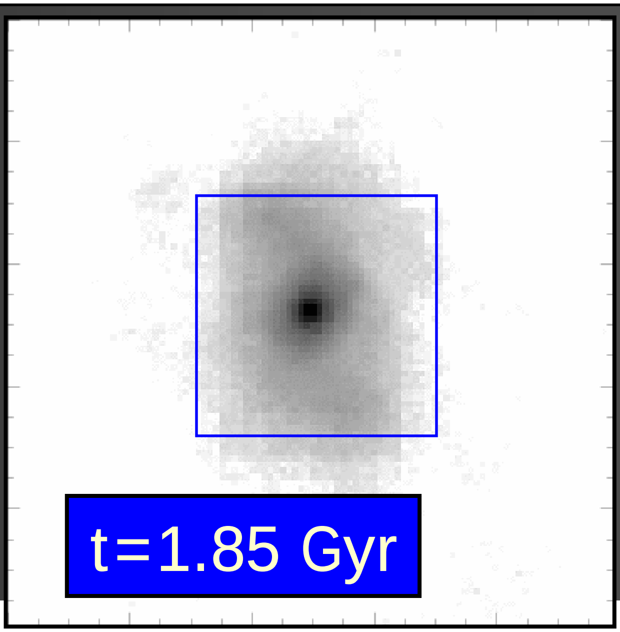
t=1.8 Gyr

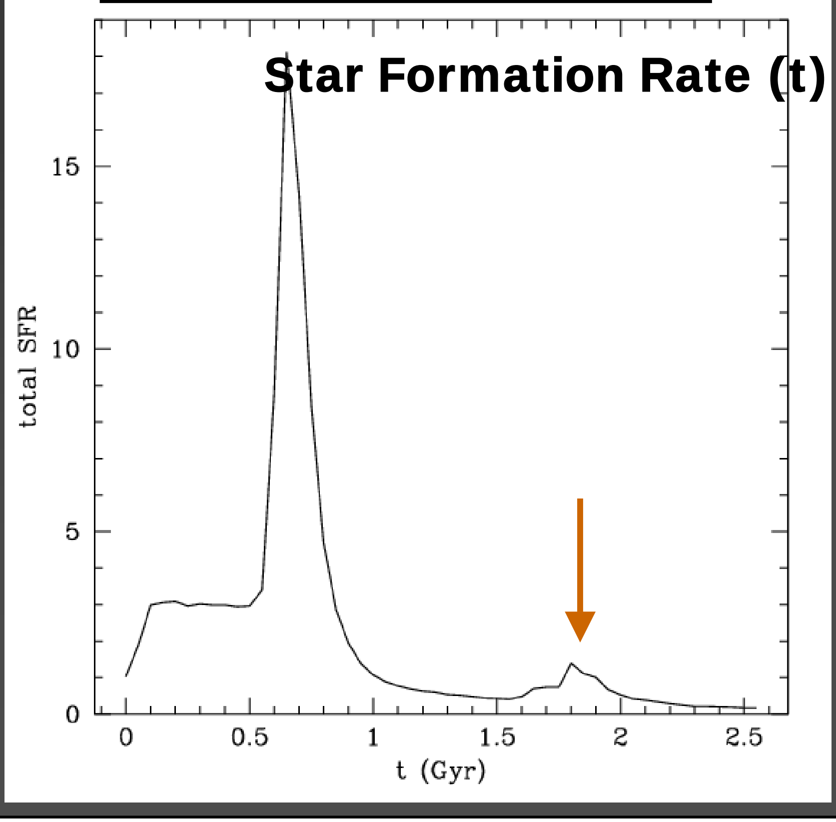


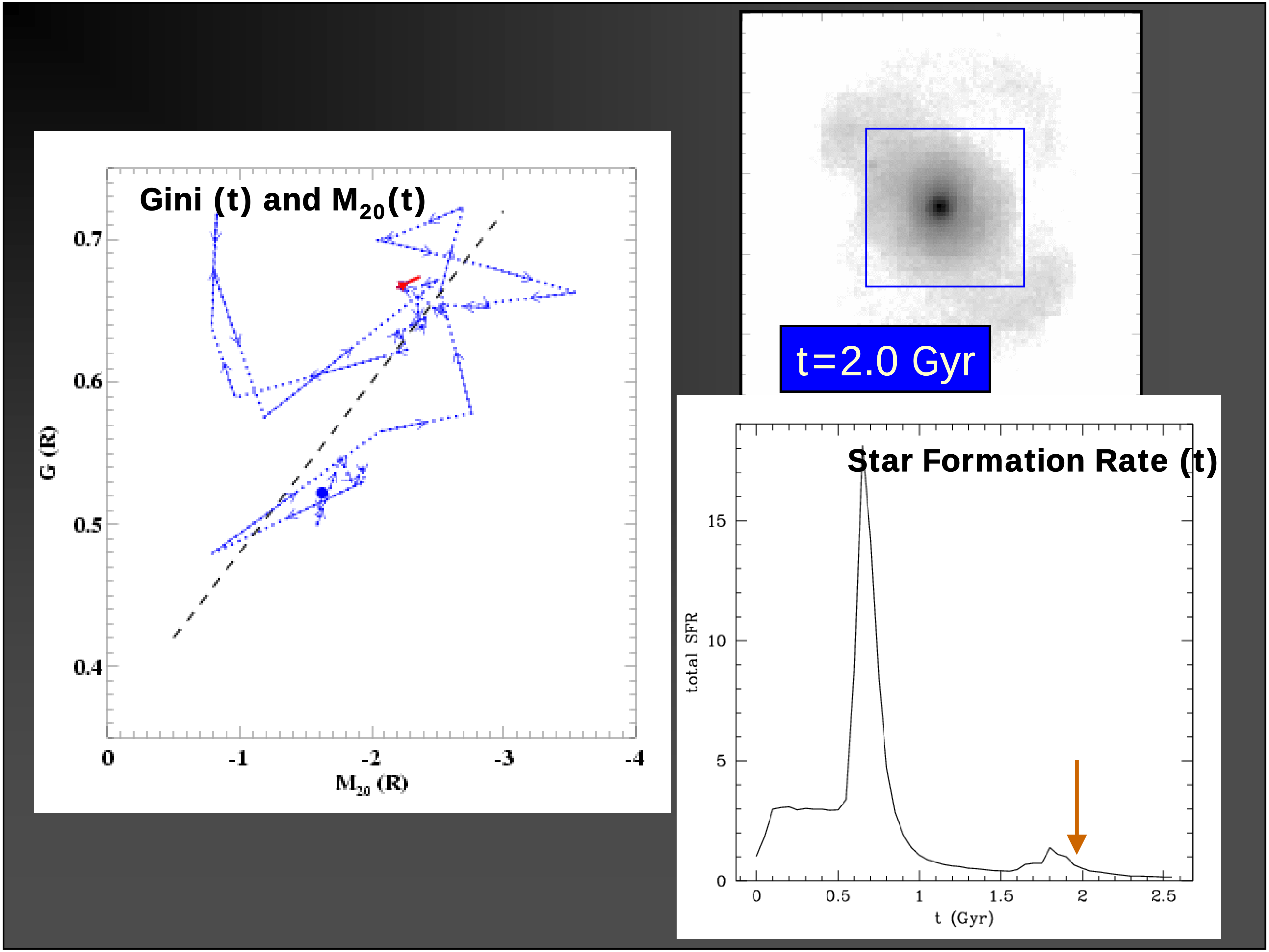
Star Formation Rate (t)
15
10
5
0
total SFR
0
0.5
1
1.5
2
2.5
t (Gyr)

nuclei finally merge



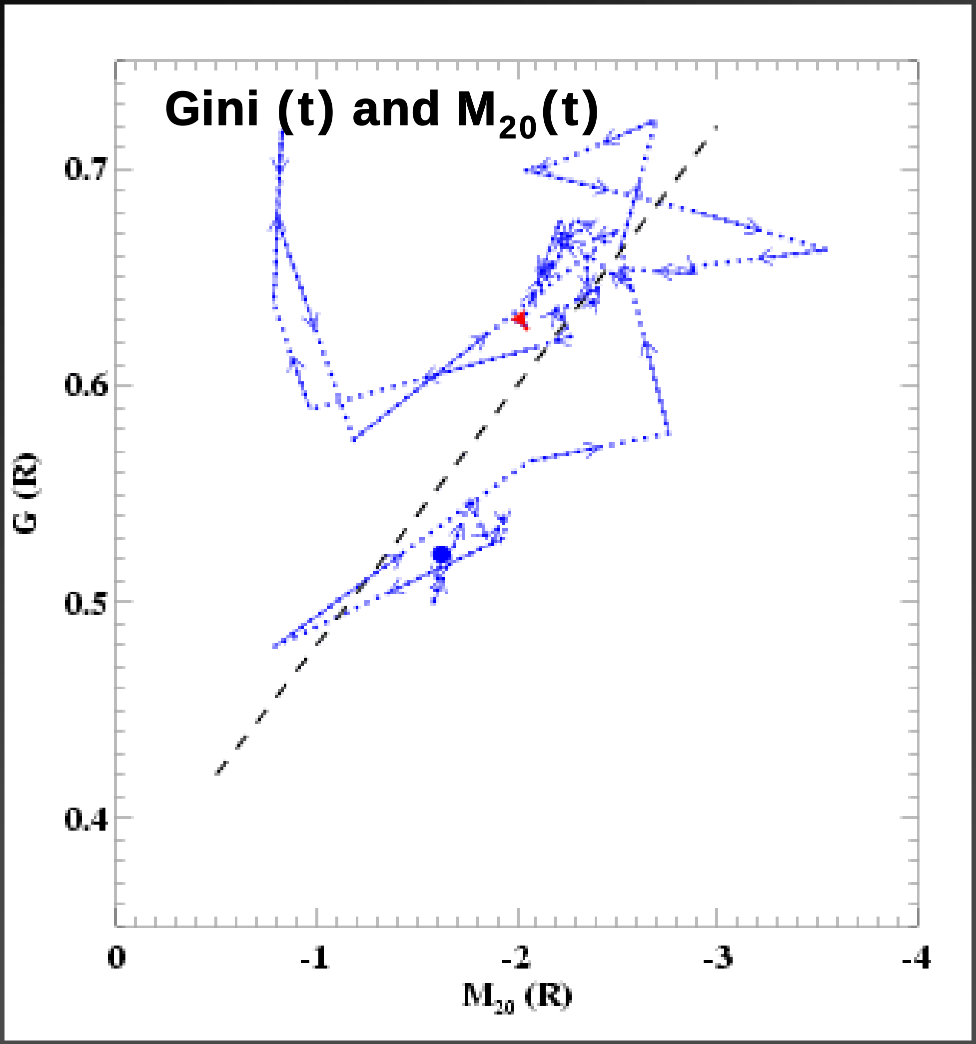


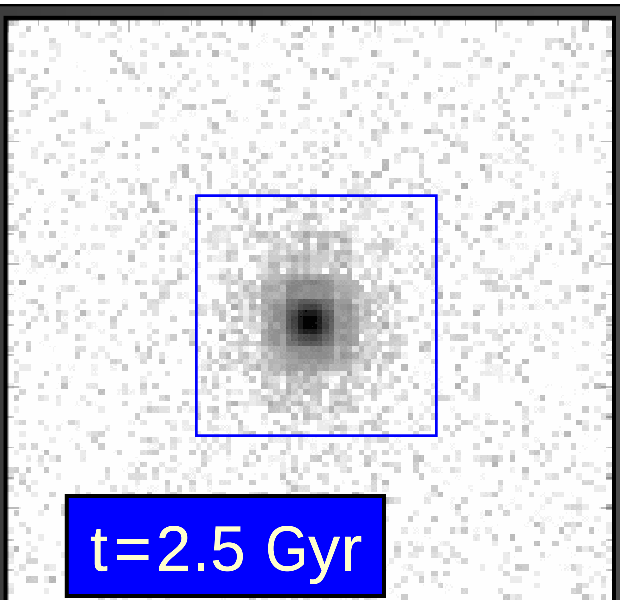


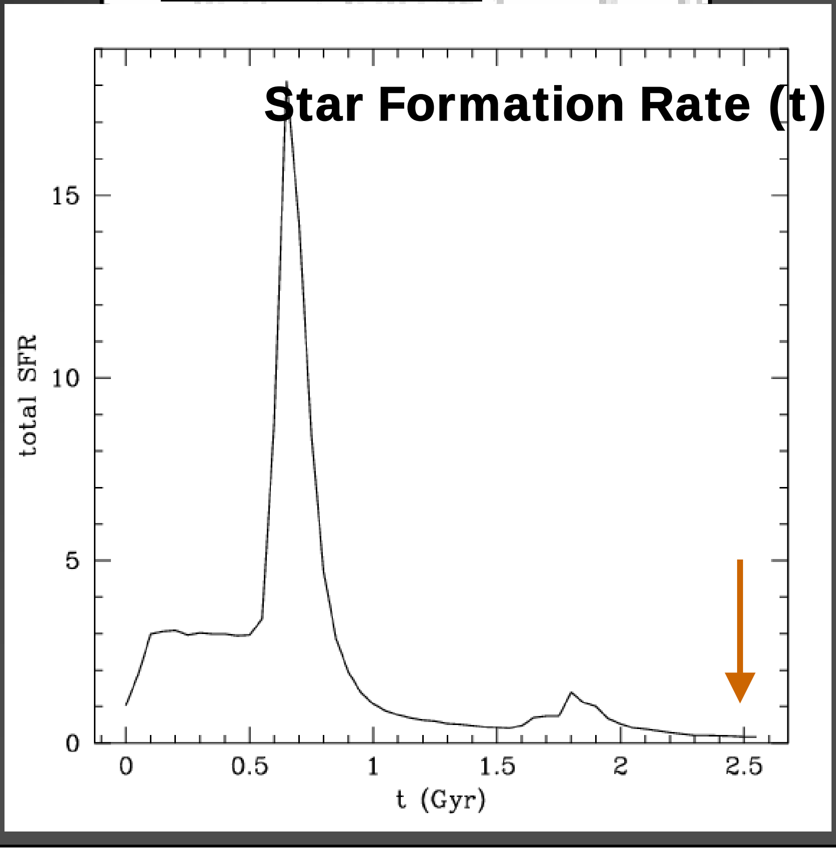


Gini (t) and M_{20}(t)
0.7
0.6
0.5
0.4
G (R)
0
-1
-2
-3
-4
M_{20} (R)
t=2.0 Gyr
Star Formation Rate (t)
15
10
5
0
total SFR
0
0.5
1
1.5
2
2.5
t (Gyr)

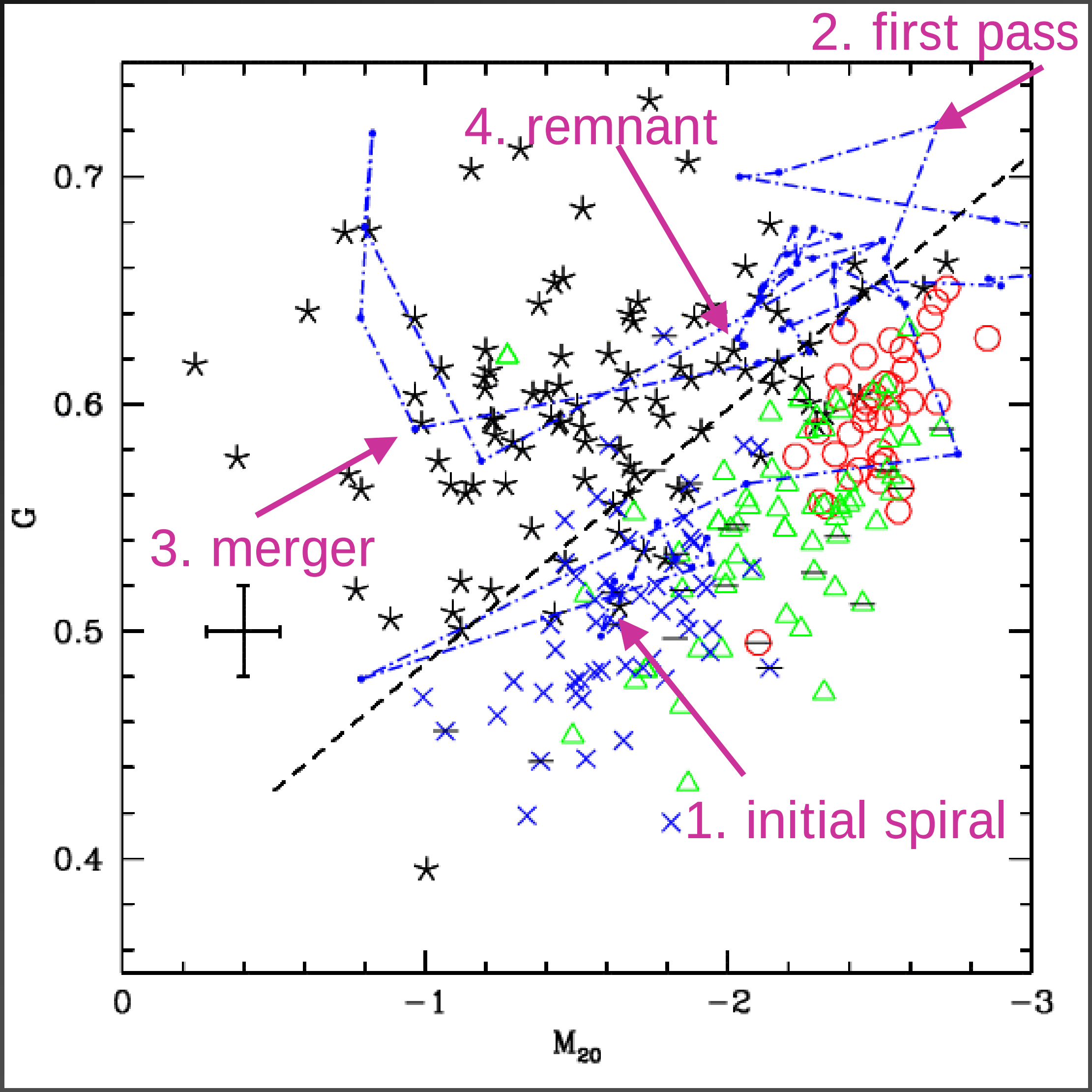
merger remnant/E?







all together...



Summary

- normal galaxies follow well-defined G-M_{20} sequence
- merger candidates (ULIRGs, LBGs) fall above this relation
- initial merger simulations agree with G-M_{20} obs

  (more tests to come)

Summary

- normal galaxies follow tight G-M_{20} sequence
- merger candidates (ULIRGs, LBGs) fall above this relation
- initial merger simulations agree with G-M_{20} obs

  (more tests to come)

→ Gini Coefficient + 2nd order Moment
are powerful yet simple new tools
to classify galaxy morphologies + id mergers

lots of work to do!

Some of the work in progress now...

Morphologies with Keck DEEP2 survey

- morphologies of close/interacting pairs (w/ L. Lin)
- LIRGs/ ULIRGs at z ~ 1 –2
- [OII], colors v. G, M20
- evolution in "normal galaxy" G-M_{20} reln out to z~1
- detailed comparison with models (→ merger rates)

Also HST, GALEX, Spitzer

overall summary: what questions do we need answered?

- What determines the efficiency of star formation in quiescent galaxies? in interactions/bursts?
- What determines the amount of light absorbed and re-radiated by dust in galaxies?
- How much small scale power is there? Can we reconcile CDM's 'small scale crises' with observational evidence for early star formation and re-ionization?
- How bright are collision-induced starbursts at various wavelengths, and what is their morphology